Distributed Infrastructuring and Innovation

An ethnographic enquiry into collaborative modes of work in an internet of things ecosystem

Andrés Domínguez Hernández

PhD Science and Technology Studies

The University of Edinburgh

2020

Abstract

Emerging low-power wireless networks are being used for a range of data collection systems such as asset tracking, environmental monitoring, smart agriculture and smart city facilities. The relatively low costs of hardware components, modular network architectures and open standards are allowing a diversity of new actors to engage with the construction of 'internet of things' (IoT) networks and applications. Various branches of research within management studies, critical theory, design theory, feminism and science and technology studies (STS) have explored collaborative modes of technology development among heterogeneous groups of actors and addressed questions of how and why users become involved in technology development. There is however scant empirical and theoretical work on the involvement of 'users' and other non-conventional actors in contemporary data-oriented infrastructures such as the IoT. Conjointly, most policy roadmaps concerning the rise of pervasive data networks rely primarily on industry-oriented analyses and quantitative forecasts and hence remain blind to the involvement of non-corporate actors in the shaping of technological futures. Building on an STS-inflected framework, this study contributes to bridging this gap with a micro-level enquiry into collaborative work practices in the realm of the IoT.

This thesis explores the case of *The Things Network*, an initiative with the mission to build low-power wireless networks in a decentralised fashion with a strong reliance on geographically dispersed contributors. The initiative is far removed from traditional top-down infrastructure implementation strategies and faces a range of ambivalences related to organisation, growth and sustainability. The study is concerned with the questions of what types of work, social organisations and artefacts are subsumed in the emerging ecosystem? why/how contributors organise and operate local networks? whether and how control is exerted by the project owners? and how the uneven actions of users and other non-conventional actors are implicated in the generation of technical improvements and outcomes? The methodology comprised a multi-site ethnographic exploration over two and a half years with the practitioners contributing variously to the construction of data networks and the development of IoT solutions within the initiative.

An ecological analysis is developed, drawing on theories and concepts from infrastructure studies and the social shaping of technology framework. The evolution of the initiative is traced throughout the stages of inception, early scaling up and global expansion. Through casting low-power networks as ‘data infrastructure’, the analysis foregrounds the challenges and dilemmas associated with scaling up in the context of decentralisation. The concept of ‘distributed infrastructuring’ is proposed as a means to capture the orchestration of the piecemeal work of disparate and dispersed actors operating autonomously with a common network architecture. The findings suggest that this mode of infrastructuring is symptomatic of an industry trend towards an increasing fragmentation and distribution of professional development activities among a range of actors. We conclude that policy and practice would benefit from a nuanced recognition of the diversity of contributions, positionalities and preferences in the broad landscape of data-driven technologies.

Lay summary

The last decades have seen a fast-paced development of information and communication technologies. One of the most remarkable advances is the prospect of internet connectivity extending its reach to the connection of physical objects –a trend that has been dubbed 'the internet of things' (IoT). IoT networks are being used for locating and tracking objects, gathering data about the body, the environment or industrial equipment, monitoring utilities through smart meters, enabling smart city services, and a range of other data-driven applications. Industry actors are spearheading the shaping of this technological trend and are involved in the business of forecasting and harnessing its market potential. Particularly in the developed world, policymakers have embraced a discourse of promoting sustainable development through the modernisation, optimisation and digitisation of industry, agriculture, energy systems and urban spaces. Such strategies have been embedded in future-oriented roadmaps such as Industry 4.0, the Fourth Industrial Revolution or the Next Generation Internet. While the transformative potential of these visions comes with high expectations, the heightened focus on digitisation and the monetisation of data have also raised concerns about privacy, security, digital divides, concentration of power and an economy powered by surveillance. By and large, the visions of industry actors and policymakers are informed by macro-level analyses and although public consultations and so-called 'human-centred' approaches are called for, there seems to be a lack of engagement with the needs of the implicated beneficiaries of 'smart' systems.

Against this backdrop, I have taken an interest in alternative visions of the IoT to those advanced by established industry actors. Bottom-up approaches raise important questions not only in regards to the ownership and control of data, but about the feasibility of participative and collaborative modes of involvement. One might look for instance at the free and open source movement and community wireless networks which have been relatively successful in their collaborative methods to engage with technological development. Indeed, some of the principles and modes of work of these developments are still largely exercised and are influential in the context of the internet of things.

This study looks into how emerging open sensor networks, low-cost hardware and open source software are being adopted by professionals, independent developers, entrepreneurs, researchers and enthusiasts for engaging with the IoT. In particular, I have traced the evolution of an internet of things initiative founded in Amsterdam (The Things Network), which started as a non-profit organisation with the aim of building an open data network with the help of contributors around the world. Inspired in the methods of anthropology, I observed and engaged with the work of developers, engineers, designers, network architects and implementers, and interviewed various members and contributors involved with the initiative for a period of two and a half years. Throughout this period, the project has seen a steep learning curve and undergone various phases of adaptation of its aims.

This study uncovers the challenges and dilemmas experienced by the project owners and external contributors in the construction of decentralised data networks. In order to deal with the complexity of such an endeavour, I propose to understand the internet of things as infrastructure and study its social, temporal and spatial dimensions. The findings of the research point to some of the strategies that have been used in the pursuit for a sustainable model, but also indicate a concerted interest from industry actors in 'delegating' certain innovative activities to a wide range of actors. The development of IoT applications and solutions demands the coordination of the work of experts, implementers and developers who may well belong to different organisations and domains of expertise. In light of a highly contested battleground of smart technologies, this study suggests that a nuanced recognition of the diversity of motivations and distinct forms of involvement is needed to inform regulation and policy.

Acknowledgements

This work could only be accomplished through the intellectual, affective and financial support of many different people and institutions throughout the years.

I would like to start by expressing my deepest gratitude to my supervisors Prof Robin Williams and Dr James Stewart, who have offered me invaluable guidance, mentorship and encouragement during a long doctoral journey. Not only their insightful critiques and comments have helped to develop various of the key arguments of this thesis and reach its final form, but they have also supported my involvement in highly enriching spaces which have directly and indirectly benefited the research process. I am especially grateful to both for inviting me to join the EU2020 CANDID research project on sensing infrastructures and the IoT ethics and governance action group at the University of Edinburgh. In connection with these projects, I must also thank Dr Antti Silvast for his comments on the early stages of fieldwork and literature recommendations, and Prof Charles Raab for his thoughtful encouragement and advice on the process of writing.

I am equally indebted to each of the members of staff at The Things Network headquarters at the time of my involvement. This project could not have been possible without their generous help and they have also made the experience of fieldwork an immensely rewarding one. I would especially like to thank Wienke Griezman, Johan Stokking, Laurens Slats, Rishabh Chauhan and Daniel Gómez for facilitating my forays into the field. Likewise, I am grateful to all the participants who agreed to take part in the interviews for kindly and openly sharing their stories with me. I hope this thesis offers a fair and faithful account of their contributions.

It has been a privilege to have shared the joys and struggles of the PhD journey with my fellow Latin-American contemporaries and good friends José Gómez, Andrey Elizondo, Antonio Ballesteros, Rodrigo Liscovsky and Óscar Moreno with whom I hold a shared cultural and intellectual positionality in academia. Our stimulating discussions and collaborations in exploring alternative ways of doing STS have influenced a great deal of this research. I must also thank Vassilis Galanos for a much cherished birthday present which inspired parts of this study and for kindly connecting me with fellow academics in Berlin; Arjen van der Heide for his ingenious contributions to the interview transcription process; and all those within the STS community and beyond who offered their comments and suggestions to presentations and early drafts.

I am also enormously thankful to the wonderful people who made Edinburgh my second home and those who despite the geographical borders have been a lasting source of care, moral support and companionship throughout the years. I would like to express my heartfelt thank you especially to Evina, Andreas, Mario, Ewan, Dave, Mengyao, Vicente, Lukas, Cat, Camilo, Maria Paz, Celine, Silvana, Carla, Anderson and Diana for their friendship over the last years. I am equally indebted to Rishabh and Capucine for a most nourishing period of lockdown writing, food for thought and conviviality in the midst of the pandemic.

To my family, especially my mother, grandmother and brother, I am eternally grateful for their selfless love and words of care, warmth and encouragement despite the long physical and temporal distance. All of my achievements are theirs; becoming a first-generation academic is a great honour which owes entirely to their efforts. I am also immensely grateful to Julia not only for generously proofreading a significant part of this thesis but for being an incredibly patient, considerate and loving partner and keeping me physically and mentally healthy during the most challenging periods of the PhD.

Last but not least, this research would have been impossible without the financial support of an unprecedented 'Universities of Excellence Scholarship Programme' by the Ecuadorian Secretariat of Higher Education, Science, Technology and Innovation (SENESCYT).

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ABINC: Associação Brasileira de Internet das Coisas (Internet of Things Brazilian Association)

ANT: Actor-Network Theory

API: Application programming interface

ARPANET: Advanced Research Projects Agency Network

CAD: Computer-aided design

DIY: Do it yourself

EDA: Electronic design automation (software)

ERP: Enterprise resource planning

FOSS: Free and open source software

FPGA: Field-programmable gate array

GDPR: General data protection regulation

GNU: GNU's not Unix

GPL: General public license

HCI: Human-computer interaction

HTML: Hypertext Markup Language

I/O: Input/Output (in computing)

IaaS: Infrastructure as a Service

ICT: Information and communication technology

IEEE: Institute of Electrical and Electronics Engineers

ILSR: Institute for Local Self-Reliance

IoT: Internet of things

IOTRIS: Internet of Things Research & Innovation Service (University of Edinburgh)

IS: Information Systems

IT: Information Technology

LoRa: Long-range (low-power wide-area network protocol)

LoRaWAN: Long-range wide-area network

LPWAN: Low-power wide-area network

MIT: Massachusetts Institute of Technology

NFC: Near-field communication

OSHW: Open source hardware

OSI: Open systems interconnection

PaaS: Platform as a Service

PCB: Printed circuit board

PD: Participatory design

R&D: Research and development

RFID: Radio-frequency identification

SaaS: Software as a Service

SCOT: Social construction of technology

SI: System Integrator

SLA: Service-level agreement

SME: Small and medium-sized enterprise

SMS: Short message service

SoA: Software-oriented Architecture

SST: Social shaping of technology

STS: Science and Technology Studies

TCP/IP: Transmission control protocol/Internet protocol

TTI: The Things Industries

TTN: The Things Network

UCD: User-centred design

UDP: User datagram protocol

Chapter 1 – Introduction

Motivation

This research project is rooted in a personal interest in electronics, innovation and the internet. As a telecommunications engineer back in 2009, I was professionally involved with the implementation of large fibre-optic and mobile networks in Ecuador. This experience offered me first-hand contact with the very material aspects of internet infrastructure, the mechanics of its deployment, the technicalities of its operation and the numerous challenges of maintenance and repair. Later, thanks to a scholarship, I pursued a master's degree in technology and innovation management in the University of Queensland, Australia, where I engaged with strategic management, evolutionary economics and processes of intellectual property protection and commercialisation of technology.

Over the subsequent years, I got involved with establishing innovation programmes in the Ecuadorean public sector. First, at a brand-new science and technology park, where I helped to establish a technology commercialisation unit and a business incubator; and later, as director of technology transfer in the Ministry of Science, Technology and Innovation, where my work revolved around fostering technological entrepreneurship and links between industry and academia. As much as these experiences were enlightening, they were also highly challenging as conflicting views from policymakers collided in the attempts to facilitate innovation in the country. At this stage, the efforts to help SMEs innovate were hampered by the prevailing ideology that stable foreign technologies needed to be imported, adopted and learned before we would be able to produce our own. I became deeply concerned with untangling the dominant assumptions held by policymakers about science, technology and innovation, which sparked my interest in formally investigating these issues.

I was drawn to the field of Science and Technology Studies (STS) for its treatment of technology and innovation as sites of critical enquiry and its impetus to engage with policy. In 2015, I secured funding to conduct a Master's and a PhD programme within the STIS (Science, Technology and Innovation Studies) department at the University of Edinburgh. During the first year, I delved into some of the prominent theories, methodologies and debates in STS. Conjointly, I reflected on the issues that motivated my incursion into research, my experiences as an engineer and my understanding of technology. Particularly inspiring at this stage were Lucy Suchman's feminist critique of corporate innovation agendas and her work on the politics of everyday professional practices (Suchman, 1993b, 2002b; Suchman and Bishop, 2000).

In due course, I chose to pursue my interest in innovation not by deconstructing the drawbacks of policy, but by engaging with the professional practices surrounding information technology and with alternative models to the *status quo*. As a starting point, I took an interest in small organisations and individuals endeavouring to bring new ideas and solutions to fruition by leveraging the affordances of Big Data, wireless technologies and hardware development tools. Eventually, as a result of my early explorations and conversations with practitioners, I decided to focus on the capacity of individual developers to innovate in the context of a growing digitisation of industrial processes, human activity and the environment. This study is the result of my ambition to open up non-conventional sites of action to scrutiny, and in so doing, reflect on the dominant discourses on innovation.

Background

The promise and perils of the internet of things

Within three decades since the creation of ARPANET in the 1960s, there were several major milestones in the history of the internet such as the rise of standard-based architectures, the OSI layered model, the development of TCP/IP and HTML, and the invention and subsequent mass-adoption of the World Wide Web (Abbate, 1999). Then at the turn of the millennium, two developments stand out. On the one hand, the use of the internet underwent a shift towards enhanced user interactivity and participation on the web at a global scale, giving way to the rise of today's gargantuan social network platforms and the so-called 'web2.0', but also to collaborative and dispersed modes of knowledge production facilitated by the internet (I shall return to this point later).

On the other hand, internet connectivity began expanding beyond the realm of personal computers into other spheres of life owing to advances in communication technology and chip manufacturing. Various future visions at the dawn of a new era of pervasive internet connectivity and ubiquitous computing were touted by commentators and science fiction writers (see e.g. Weiser, 1999). However, the advent of 3G mobile communications along with the mass adoption of smartphones is perhaps the most concrete early manifestation of this trend. As Manuel Castells points out in *The rise of the network society*, 'the networking logic epitomized by the Internet became applicable to every domain of activity, to every context, and to every location that could be electronically connected' (Castells, 2010b, p. 52).

Over the last two decades, this stage in the evolution of the internet became variously registered in terms such as 'ubiquitous computing', 'ambient intelligence', 'cyber-physical systems', and perhaps more prominently 'the internet of things'. Far from describing a coherent system, these terms subsume a multifarious array of rapidly changing technological developments revolving around the digitisation and automation of industrial equipment, urban spaces, consumer products, energy grids, farming and other imaginable spheres of modern life.

More recently, discourses of radical transformations underpinned by the convergence of developments in information technology (e.g. Big Data, machine learning, internet of things) has been mobilised by policymakers and world leaders in the developed world. Three noteworthy examples are the foreshadowing of a fourth industrial revolution at the 2016 WEF meeting at Davos (Schwab, 2016); the German industrial roadmap known as industry 4.0 (Plattform Industrie 4.0, 2019); and the European Commission's Next Generation Internet agenda (EC, 2016). These high-level roadmaps comprise industry-driven attempts to imagine and steer technological trajectories, ensure interoperability within heterogeneous ecosystems and devise strategies for achieving medium-term targets (e.g. Sustainable development Goals).

Policy debates are primarily informed by future-oriented industry analyses with a focus on forecasting market behaviour, patterns of adoption, numbers of connected devices, technology life cycles and business models. Innovation within these policy recommendations is often framed around the desirability of openness and participation. While big industry actors are central in the drafting of policy proposals the idea that a diversity of stakeholders is desirable for the success of new technologies is a recurring one and indeed a political leverage for public support. A working document from the European Commission reads:

> According to the Digitisation communication, European companies should strive for leadership in IoT platforms allowing them to manage

> an ecosystem including SMEs, researchers, entrepreneurs and innovators that is anchored in Europe. Successful platforms should as well be open. This way they can achieve critical mass, allowing platform owners to encourage third party developers, suppliers and users, as well as competitors to build application and services that run on them –while also preserving the role of leading European stakeholders in key markets (European Commission, 2016, p. 25).

The need to take humans, citizens and users into account is also frequently brought up if only tangentially, based on ethical and moral reasons. The document continues:

> It is commonly recognised that IoT has the potential to drastically improve our personal lives, our work places and our industrial / manufacturing efficiencies and capabilities. There is, however, a concern that IoT may lead to alienation because of objects capable of 'talking' to one other and to lose sight of human preferences. In order to ensure that IoT improves lives by empowering people instead of transforming them into hostages of technology, Commission services are of the opinion that certain safeguards might need to be put in place or current safeguards need to be made more specific (European Commission, 2016, p. 27).

While there is much optimism around new data-oriented technologies, the visions about not-so-distant futures of smart systems enabled by unprecedented levels of data collection have also sparked public concern, not least due to the increasing concentration of power by large technology firms. High-tech smart city proposals have, for instance, been received with scepticism over their top-down blanket proposals and heightened potential for undermining privacy and democracy (Sennett, 2012; Sadowski, 2017; Krivý, 2018). Taking this issue to a broader scale, Shoshana Zuboff (2019) has more recently forewarned the consolidation of new mechanisms of extraction and appropriation of large amounts of data for purposes of behaviour prediction and manipulation –a stage she has dubbed Surveillance Capitalism. IoT systems play a key role in this scenario as they become enabling infrastructures for the digitisation of objects, people and the environment.

The growing interest in data collection and commodification have placed the internet and the rise of Big Data at the centre of debate in the spheres of ethics, privacy and governance (Lyon, 2014; Ruppert, Isin and Bigo, 2017; Flyverbom, Deibert and Matten, 2019). It thus seems imperative to unpick the frequently invoked virtues of modernisation, open innovation and user-centredness that frequently accompany future-oriented discourses at the expense of underplaying potential risks. Notwithstanding the widespread language of 'human-centred' or 'user-centred' technology, which is mostly underpinned by user research and public consultations, the dominant industry-oriented discourse draws heavily on macro-economic understandings of innovation which focus on key influential institutional and entrepreneurial actors. Yet these views might fail adequately to recognise the agency of users, alternative models of technology production and the perils of emerging data-intensive technologies.

Bottom-up, decentralised and alternative forms of production

The top-down views of technology discourses can be counterposed both with the track of alternative/bottom-up propositions in the history of the internet and with emerging distributed forms of organising technology development. As mentioned earlier, the internet has enabled and been shaped by modes of dispersed collaboration and knowledge production which also challenged age-old notions of intellectual property protection and ownership. The free and open source software (FOSS) movement is perhaps the most salient example. The open source model of production sparked the interest of scholars across various disciplines and helped to recognise the potential for ostensibly decentralised and unconventional modes of innovation. Scholars in management science and economics, for instance, have suggested that open source modes of collaboration resemble a 'gift economy' of sorts enabled by non-transactional relations of work and exceptionally low marginal costs of distribution and replication of information resources (Bergquist and Ljungberg, 2001; von Hippel, 2002). Some of these alternative practices later evolved into streamlined and formalised models of work and have been 'mainstreamed' to a large extent in the corporate world (Landau, 2010). Open source principles and models have also been tried out, with varying degree of success, in other domains including culture, biotechnology and hardware (Hope, 2008; Fisher *et al.*, 2015; Giannatou *et al.*, 2019).

Alternative bottom-up models of collaboration are also found in the construction of internet infrastructure. Several different instances of community wireless networks have emerged around the world in response to the need to provide with internet coverage in underserved areas. While many of these efforts face difficulties and struggle to survive, there are various examples of successful community-led wireless networks (Lawrence *et al.*, 2007; Frangoudis, Polyzos and Kemerlis, 2011; Söderberg, 2011). These initiatives seem to depart from the traditional top-down approach underpinned by wherewithal, economies of scale and vertical integration.

The rise of platforms in a multitude of domains, albeit not fundamentally bottom-up or counter mainstream, is a critical turning point worth mentioning in this ongoing narrative. The Web 2.0 and internet platforms have been usually associated with a rhetoric of empowerment, participation and democratization (Beer, 2009). Yet more recently, there are in fact growing apprehensions about the unparalleled levels of data extraction of large platforms such as Google, Amazon and Facebook (van Dijck, 2013). While today's digital platforms are at the centre of the regulatory and conceptual debate, they started as rather simple services locating themselves as a point of passage between otherwise dispersed producers and consumers by offering them a host of resources (Constantinides, Henfridsson and Parker, 2018). Platform-based ecosystems constitute a new way of organising innovation insofar as they open up information systems to a diversity of actors by adhering to the principles of open source and open innovation. A wave of empirical and theoretical research around the 'platformisation' of the web, particularly in the fields of information systems, management, economics, regulation and media studies, has arisen in the last decade (see Altman and Tushman, 2017; Cennamo and Santaló, 2019; Constantinides, Henfridsson and Parker, 2018; Hanseth and Bygstad, 2018; Helmond, 2015; Bauer, 2014; Ballon and Van Heesvelde, 2011).

Building on the experiences of prior developments such as FOSS and community wireless networks and through exploiting new architectures, technological affordances and business models, alternative ways of organising work and innovation activities are also being tried out in the construction of IoT applications and sensor networks. Control and ownership over the data, citizen science initiatives, academic research or simply an optimisation of the cost of deployment are some of the motivations behind these efforts. This thesis focuses on one such attempt with the intention of uncovering the challenges of building decentralised data networks and investigating the involvement of 'non-conventional actors' in technology production. The phrase 'non-conventional actors' is used here as a way to characterise those actors located outside the typical firm-based loci of ICT development including, but not limited to, users, independent developers, citizen science groups, hobbyists, techno-enthusiasts, researchers and SMEs.

The landscape of the internet of things is, however, a highly complex one, with applicability in a wealth of domains and encompassing a myriad of technologies and players. To locate the empirical focus of this study, some demarcations of the terrain are in order.

In the wake of the internet of things paradigm, existing communication standards have seen an extension of their use to the realm of physical objects, but also, new wireless technologies oriented specifically to sensors have emerged in recent years. These standards have been bundled up under the rubric of LPWAN (low-power wide-area network) and fulfil a set of technical requirements that are not met by the most commonly used wireless technologies such as WiFi and cellular, namely low energy demands paired with long-range connectivity. Among the competing standards, LoRaWAN, developed by an international consortium[1], has been promulgated as an open specification thereby engendering an ecosystem of large and small players.

Within the emerging space of LPWAN, a non-profit initiative known as *The Things Network* (TTN) has shown remarkable success in terms of adoption of the LoRaWAN standard and the generation of applications. The distinct approach of TTN is to offer a decentralised open-source network architecture while the construction of the physical infrastructure is delegated to contributing developers around the world. This thesis builds on an in-depth exploration of the case of TTN and is concerned with the following questions:

1. What are the types of technical work, social organisations and technological offerings produced within the TTN ecosystem?
2. What are the factors influencing the decisions to initiate and operate local TTN networks, and what are the mechanisms for aligning and coordinating work between geographically dispersed actors?
3. To what extent are coordinators able to steer the scaling-up and trajectory of the TTN initiative at local, regional and global levels, and what are the specific strategic decisions aimed at succeeding in this endeavour?

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[1] The LoRa Alliance was formed in 2015 and is funded by large industry actors such as Semtech and Cisco

4. How do dispersed forms of work lead to the production of innovations and durable networks?

The first aim of this thesis is to make sense of the emergence and growth of a decentralised internet of things initiative and explain the involvement of users and other non-conventional actors in innovation. The second aim is to offer insights to a non-academic audience, particularly those inhabiting the field of study, who may find critical perspectives illuminating for the task of grappling with governance and identifying sensible areas of intervention. In highly experimental contexts, a critical enquiry may help to shed new light on emerging phenomena, dilemmas and controversies between actors, which could prove helpful for design and decision making. In this thesis, I seek to address these goals through an analysis informed by an in-depth exploration of the field and theories from STS and infrastructure studies. A micro-level exploration is proposed in order to access the diversity of actors involved in the construction of IoT networks.

A sociotechnical approach to innovation

To address the research questions constructively, it seems crucial to unpack the discourses of innovation and, in particular, the prevalent technology-oriented views that permeate much of the rhetoric around the internet of things. The examples of collaborative and distributed technology development seem to counterpose the commonly accepted model that technology is mostly produced in a pipeline: from the lab to production to commercialisation and finally to use. Indeed, some corporate actors have embraced forms of collaboration with complementary and competing firms. In recent years, the notion of 'open innovation' has emerged as the hallmark of enhanced interfirm collaboration based on the sharing of information, intellectual property and R&D capabilities in a way that challenged conventional secrecy-based competition (Enkel, Gassmann and Chesbrough, 2009).

But another mode of collaboration identified within strategic management has been one between designers and users. Some authors within studies of innovation have shown that users could become highly invested in coming up themselves with improvements to products and services (see von Hippel, 2005). The role of users in the success of technologies has indeed been an ongoing source of interest within management and design theory. In the domain of ICTs, practitioners and scholars have promoted a focus on users since the 1980s with the purpose of gathering relevant information from the contexts of technology use. This impetus has given way to the popularisation of the terms 'user innovation' and 'user/human-centred' design (Norman and Draper, 1986; Morrison, Roberts and von Hippel, 2000; Flowers *et al.*, 2008). The idea of designers productively collaborating with users signals a break with the mechanistic models that portray innovation as a straightforward and linear process. However, the 'user innovation' and 'user-centred' approaches have been concerned mainly with developing prescriptive schemes and toolkits for firms, designers and policymakers to manage and internalise users' inputs while falling short of engaging with the broader social and political issues that surround innovation.

In this thesis, I draw on theories advanced within the field of Science and Technology Studies which offer a point of entry to deal with the social, political and economic implications of technological development and innovation. The interdisciplinary field of STS been preoccupied with dealing critically with the complexities of science and technology in modern societies. In the study of technological change, a central aim of STS scholars has been to advance a critique of technological determinism –the widely-influential view that technology, due to its intrinsic properties, has direct and discernible effects in society. Techno-determinist assumptions often underpin policy discourse and a linear framing of innovation as a straightforward process from basic science through applied research and development to commercialisation. This view conceives technologies as finished and readily available for use while being blind to the agency of users and foreclosing the possibilities for alternatives and unexpected outcomes. A shared premise in STS scholarship is that technology and society should not be understood as separate from one another, but instead as highly entangled and mutually shaped (Williams and Edge, 1996; MacKenzie and Wajcman, 1999; Jasanoff, 2004). Innovation, far from straightforward, is a highly uncertain process involving not only the creation of technically-sound artefacts but a range of complex social interactions, negotiations, alliances, conflicts and tensions. The descriptor 'sociotechnical' is thus frequently used to register the entanglement of technology and society.

Feminist scholars in STS have been widely influential in their critique of innovation by problematising both the male monopoly of technology discourse and practice and the gendered ways in which artefacts are developed and used (Cockburn, 1993; Wajcman, 2010). The latter line of enquiry has challenged the dominant designer/user, and production/consumption discursive divides by stressing the sociotechnical intertwining of all stages of technological development. Lucy Suchman writes:

> Within traditional discourse anonymous and unlocatable designers, with a license afforded by their professional training, problematise the world in such a way as to make themselves indispensable to it and then discuss their obligation to intervene, in order to deliver technological solutions to equally decontextualized and consequently unlocatable 'users.' This stance of design firm nowhere is closely tied to the goal of construing technical systems as commodities that can be stabilized and cut loose from the sites of their production long enough to be exported en masse to the sites of their use. (1993b, p. 27)

This is a helpful approach to inquire the relationship between users and technology insofar as it calls for a recognition of the numerous ways in which users and consumers enact their demands or discomforts with technology. As demonstrated in studies of technology in use (e.g. Silverstone and Hirsch, 1992; Kline, 2003; Haddon, 2004), users reconfigure and appropriate artefacts in ways that might differ from those imagined by designers. Moreover, users might assume different roles and engage with practices that would otherwise be exclusively attributed to designers (Oudshoorn and Pinch 2003; Suchman 1993). The task of assessing the wealth of heterogeneous contributions, however, poses numerous practical challenges for research. Indeed, the sites where relevant work takes place may be difficult to access but also obscured by the prominence of more visible sites inhabited by professional designers. The need to bring various forms of otherwise-invisible work to the fore has been at the core of feminist empirical and theoretical enquiry of technology (Suchman 1995; Star and Strauss 1999) and provides important methodological underpinnings to tackle the questions of this thesis.

Of particular significance for this study is the work of Susan Leigh Star on uncovering the various forms of technical practices hidden behind ostensibly stable large systems (Star, 1990, 1999; Star and Ruhleder, 1996; Star and Strauss, 1999). For this strand of research, taking infrastructure as a unit of analysis offers a means to scrutinise the mundane practices of implementation, maintenance and operation which are often underplayed in the discourses of innovation that centre on the efforts of entrepreneurs and inventors. As Star (1999) would have it, exploring the hidden aspects of technology is, in fact, 'a call to study boring things'. Borrowing from some of the techniques and tools from anthropology, the aim is to study large systems ethnographically with a focus on praxis. This research falls in line with Star's view that 'finding the invisible work in information systems requires looking for these processes in the traces left behind by coders, designers, and users of systems' (1999, p. 385).

The aims of this thesis are pursued through a theoretically informed analysis and an in-depth account of the different sorts of work behind the construction of IoT infrastructure and solutions. I build both on a sociotechnical view of innovation and on an ethnographic approach to weave a narrative of the construction of IoT systems. In light of the questions of this study, the ethnographic project confronts a set of issues which had to be considered for devising a research design: 1) the construction of decentralised networks entails situated work at geographically dispersed sites but also internet-mediated work; 2) IoT data-networks are complex assemblages involving diverse actors (e.g. suppliers, developers, standard organisations) and different sorts of work practices and business domains; 3) the TTN initiative is global in scale, yet it subsumes a universe of different local needs, idiosyncrasies, motivations and forms of organisation; and 4) these networks are intended to be durable and stable for a period that outlasts the current study, and hence, this is an enquiry into objects still in development.

Structure of the thesis

In the chapters that follow, I take stock of the research journey, locate the study historically and within the scholarly literature, and offer an interpretative account of the challenges, motivations and efforts of practitioners and informants involved with the TTN initiative.

In Chapter 2, I begin with a review of the most salient scholarly contributions surrounding the involvement of users and non-conventional actors in technology design and development. This phenomenon has been extensively researched from various flanks and with different agendas. Management science and design theory have focused on producing recommendations for practitioners and managers with a programme oriented towards improving design and the organisational practices of innovative firms. Critical theory and cultural studies, on the contrary, have problematised the change of paradigm towards the co-creation of goods and services as a manifestation of shifting configurations of labour brought about by post-industrial capitalism or the 'network society'. Furthermore, with roots in social justice movements in the 1960s, participatory design emerged as an interventionist proposal to the design of public space. Similar design principles were later proposed as a response to the displacement and deskilling of workers due to the introduction of computers in the workplace. Participatory design has remained highly influential as an academic field that promotes and theorises democratic participation in technology design. I also include in this review a preamble of the research on users within STS paying particular attention to the work of feminist scholars and discuss a salient branch of research within the field of Information Systems which focuses on emerging distributed systems. Finally, I review three historical markers of countercultural technology production and co-creation, which are of relevance for the contemporary landscape of collaborative development in the internet of things. These are community informatics, the free and open-source software movement, and hardware hacking. I discuss how the experiences of these past events have influenced the practices and forms of social organisation observed in the construction of IoT data networks.

In chapter 3, I outline the theoretical framework underpinning this thesis. I begin this chapter with an introduction to the interpretivist/constructivist tradition in studies of technology, and I trace the intellectual origins of three broad influential theories, namely the social construction of technology, actor-network theory and social shaping of technology. Building on the broad tenets of social constructivism, I delineate the view of innovation as a collective process and argue for the need to problematise the significance of 'users' and the nexus between the production/supply and consumption/use. I then draw on studies of infrastructure and highlight a set of methods and concepts which are helpful for understanding complex systems such as IoT data networks (Star and Ruhleder, 1996; Edwards *et al.*, 2009). In particular, I emphasise the need to take materiality into account and incorporate multiple spatial and temporal dimensions in the analysis (Hanseth and Aanestad, 2003; Bowker *et al.*, 2010; Monteiro, Pollock and Williams, 2014; Karasti and Blomberg, 2018). I propose an ecological framework for the study of the IoT that aims to map the coupling of practices and artefacts through the use of interfacing.

In Chapter 4, I discuss the research design and methodological considerations for this study. I start by reflecting on my arrival to the field and the formulation of the research questions. Next, I describe the research strategy applied throughout the study, which consisted of a multi-site ethnographic exploration of The Things Network initiative. I demarcate the boundaries of the case study and spell out the rationale behind the different tactics employed to capture the traces of work ethnographically. I then reflect on my experience of fieldwork and the process of data collection from the early efforts of negotiating access and throughout the different stages of observation and interaction with my informants. Here I discuss the challenges of accessing geographically dispersed actors and describe the specific techniques and methods which were devised for such purpose. In a section on data analysis, I elucidate the process of sorting out and coding the data as well as the abductive approach deployed for theorisation. Finally, I look into some of the ethical considerations of the research design and reflect on the implications of my intervention for the actors inhabiting the field.

The remainder of the thesis comprises three substantive empirical chapters and a concluding chapter. In chapter 5, I provide an in-depth account of the case study based on primary ethnographic data and archival documentation. I start by outlining some of the technical dimensions of sensing infrastructures and low-power wireless networks in order to locate the case within the complex landscape of IoT communication standards. I then trace the evolution of The Things Network initiative from its inception and early validation to its phases of initial expansion and further global scaling up within its four first years of operation. I continue to sketch a taxonomy of the actors inhabiting the ecosystem by categorising the different types of groups involved in establishing local instantiations of the initiative. This analysis evidences the changing strategies of the project owners in light of their interaction with a wide range of peripheral actors and highlights some of the tensions and dilemmas emerging out of such interactions.

Having mapped the social formations in the TTN ecosystem, in Chapter 6, I unpack the infrastructural dimensions of low-power networks and describe them as 'data infrastructures'. Drawing on concepts from infrastructure studies, I examine the patterns of growth and the possible lock-in effects engendered by the unusual decentralised approach of the TTN initiative. In particular, I focus on the efforts of core-developers to reckon with the promises and pitfalls of decentralisation, and I examine the dilemmas experienced by peripheral actors around kickstarting and scaling-up networks. I delve into the ongoing tensions between local and global agendas, between the short and the long-term and between control and autonomy. I propose the concept of distributed infrastructuring as an attempt to capture the orchestration of the collective and piecemeal work of disparate actors around a shared global project.

In Chapter 7, I deal with innovation as a crosscutting theme pertaining both to infrastructure-oriented work and to the generation of technological offerings. My aim in this chapter is to locate the various complementary forms of involvement in innovation within the ecosystem and identify how these are coupled to produce IoT applications and solutions. I start by problematising the applicability of the term 'users'. The project owners have produced representations of users as developers, members, initiators, integrators or contributors. Such representations flag the need for a more nuanced vocabulary that more profitably captures the uneven contributions of heterogeneous actors in information systems. Building on this analysis, I identify the mechanisms of knowledge exchange between different spheres of expertise in the ecosystem. Through looking at the materiality of technological offerings, I argue that actors operationalise the outcomes of learning through the use of modular designs and accessible components. To complement the ecological analysis, I identify four discernible spheres of expertise, namely network provisioning, hardware development, application development and system integration and sketch a sociotechnical map of the TTN ecosystem. Lastly, I propose a framework for understanding innovation in the ecosystem as overlapping cycles of learning between implementation arenas which couple their competencies through interfacing.

In the concluding chapter (Chapter 8), I bring together the findings of this thesis and assess how the research questions have been addressed. I start with a discussion about the intertwining of infrastructure work and innovation. I emphasise on the exceptionality of TTN and its value for adding to the body of literature on ICT innovation. Conjointly, I also identify commonalities with the consolidation of efficiency-driven business models based on on-demand portfolios of generic services. I reflect on how the formidable challenges of decentralisation have been hitherto dealt with through compromises and strategic alliances. I then distil the contributions of this thesis to theory, practice and research methodology and end by highlighting the limitations of this study and suggesting future avenues of research.

Chapter 2 – User involvement in technology production: a review of research and practice

Introduction

In his trilogy on the *Information Age*, Manuel Castells (1996, 1997, 1998) formulates the proposal of a 'network society', marked by an information and communication technology revolution coming to fruition at the turn of the millennium. According to Castells (2010b, p. 78) '[n]ew information technologies, by transforming the processes of information processing, act upon all domains of human activity, and make it possible to establish endless connections between different domains, as well as between elements and agents of such activities.' In the purview of a globalised network economy, ICTs facilitate new forms of communication, organisation and participation whereby geographically dispersed individuals are able to collaborate through the internet and share informational resources instantly and inexpensively. Schemes of collaboration such as free and open source software have brought about new configurations and relationships of labour and challenged age-old notions of intellectual and private property (Weber, 2004; Söderberg, 2015). In recent years, neologisms such as crowdsourcing, co-development, co-design, co-creation or prosumers have become common rhetorical means to describe emerging manifestations of user involvement in technology production. These emerging forms of internet-enabled collaboration taking place outside the boundaries of the firm are ostensibly decentralised and democratic, allowing new actors to partake in the information economy (Flowers *et al.*, 2008; Hyysalo, Jensen and Oudshoorn, 2016).

In the wake of data-oriented technologies, bottom-up forms of development and 'user-centred' policy discourses are being mobilised building on the experiences of past efforts and on design theories and innovation models. Before delving into an empirical investigation of non-conventional forms of involvement in the internet of things, it seems crucial to unpack the salience of users in technology development and locate this study both historically and within the existing debates in the literature.

In the first part of this chapter, I explore the body of literature dealing, from different scholarly traditions, with the involvement of users and other non-conventional actors in innovation. I begin with a review of theories of user innovation within management science and some of the contrasting readings with a focus on labour from critical theory and cultural studies. Collaborative technology production has also been reified by political mobilisation taking a participative, if not democratic, turn and influencing academic research and design practice owing to movements such as participatory design which I include in this review. I then look into the sphere of design practice and theory where I discuss the notion of user-centred design and more specifically the work within the field of human-computer interaction. Next, I introduce the scholarly critiques on users advanced from the field of Science and Technology Studies and inspired strongly by gender studies and feminist theories of technology. However, a theoretical discussion is later expanded in Chapter 3. Lastly, I delve into some of the concepts developed within information systems research around emerging forms of innovation associated with digitisation and platform ecosystems.

In the second section of this chapter, I trace three historical markers of bottom-up collaborative technology production in the domains of software, hardware and internet infrastructure. I start with a review of the free and open source software movement and the formalisation of its principles into the mainstream of contemporary software development. I then delve into the early days of amateur hardware hacking and the contemporary manifestations of open hardware which draw strongly on the tenets of open source software. Next, I review the early experiences of community informatics and the more recent instances of wireless community networks which propose a grassroots approach to appropriating information technology and alternative models of construction of internet infrastructure. I end this chapter by locating these events as crucial precedents that bear on the current bottom-up/collaborative efforts in the realm of the internet of things.

Users, consumers and non-conventional actors as active agents in innovation

Innovative users and new forms of labour

It has been widely recognised that users and consumers possess valuable knowledge that could be usefully acquired by designers and developers[2] to build better products. Since the early days of mass production, this knowledge has been eagerly sought by firms through market studies and consumer research and incorporated variously into value chains (Hyysalo, Jensen and Oudshoorn, 2016). Management science spearheaded the impetus on engaging with consumers and later with users with an agenda of aligning the views and ambitions of product designers with the actual needs of users. Yet, management research has also explored the possibility of individual users playing more than merely a functional role in technology production, which was central to the management research agenda in the 1970s.

The idea of 'user innovation' grew out of a series of studies of innovations where users were observed to independently carry out invention, modification, repurposing, prototyping and field testing of artefacts and manufacturing processes. In his influential seminal work, Eric von Hippel identified innovations arising primarily from users in the scientific instrument industry and the manufacture of semiconductors and electronics subassemblies (von Hippel, 1976, 1977). Von Hippel observed that users came up with more product and process improvements than those generated by engineers within firms and characterised the phenomenon as 'innovation dominated by users'.

The notion of user innovation sparked enthusiasm amongst management scholars and was further investigated in diverse areas including medical equipment (Shaw, 1985), aerospace industrial machinery (Foxall and Tierney, 1984), application software (Voss, 1985), CAD systems for printed circuit boards (Urban and von Hippel, 1988), library information systems (Morrison, Roberts and von Hippel, 2000), among others. Von Hippel suggested that a distinct category of people he labelled as 'lead users' was

[2] While much of the literature applies the term 'designer' as a generic term assigned to actors in the technology supply side, in this thesis the term 'developers' is preferred to point more adequately to the relevant practices in the domains of software and hardware.

particularly well-positioned to innovate due to their expertise and early engagement with new technologies and contexts of use. He writes: 'Since lead users are familiar with conditions which lie in the future for most others, they can serve as a need-forecasting laboratory for marketing research. Moreover, since lead users often attempt to fill the need they experience, they can provide new product concept and design data as well' (von Hippel, 1986, p. 791).

Subsequent studies in the same vein further probed the new 'user innovation' and 'lead user' theories in the context of consumer products based mainly on surveys with outdoors and extreme sports equipment (Lüthje, 2004; Tietz *et al.*, 2004; Baldwin, Hienerth and von Hippel, 2006; Franke, von Hippel and Schreier, 2006; von Hippel *et al.*, 2010; von Hippel, Ogawa and de Jong, 2011); other examples looked at modular systems (Langlois and Robertson, 1992) and automobiles (Franz, 2005). The fact that users and consumers were able to innovate by themselves was viewed by management scholars as an opportunity for firms to profit from. A new innovation strategy was thereby advanced by these studies, namely, the internalisation and commodification of promising user innovations:

> Firms can make a profitable business from identifying and mass-producing user-developed innovations or developing and building new products based on ideas drawn from such innovations. They can gain advantages over competitors by learning to do this better than other manufacturers. They may, for example, learn to identify commercially promising user innovations more effectively than other firms (von Hippel, 2005, p. 127)

User innovation research also turned its gaze to the free and open source software (FOSS) movement, a paradigmatic arena where users actively engaged with technology production. This was a promising technical field where low-cost and accessible tools had allowed both firms to develop bespoke tools, and individual hobbyists and enthusiasts to create new software. From the perspective of the economics of innovation, the question of why individual developers would freely collaborate for the production of otherwise privatised goods and still be successful was a puzzling one. A closer look at the communities of developers in open source by innovation scholars pointed at a combination of non-economic individual and collective motivations such as learning, enjoyment and reputation building (Lerner and Triole, 2000; Hars and Ou, 2002; Bonaccorsi and Rossi, 2003; Hertel, Niedner and Herrmann, 2003; von Hippel and von Krogh, 2003). However, as I discuss in the second part of this chapter, the alignment of political and economic interests are also entrenched in the success of FOSS.

FOSS became the archetypical model of what von Hippel later termed ‘innovation community’. The distinctive aspect of an innovation community was, according to von Hippel, the existence of ‘information transfer links’ which can be face-to-face but also span geographical boundaries thanks to electronic communications (von Hippel, 2005). As opposed to the concept of user innovation where knowledge exchange was seen as flowing vertically between users and producers, innovation communities entailed a more horizontal knowledge transfer between users (von Hippel, 2002, 2005). For von Hippel, the case of software (and any information good for that matter) was fundamentally distinct from the production of physical goods in that manufacturers did not get involved, thereby allowing innovation communities to have more autonomy.

The innovation studies branch has been influential in problematising the possibility of user-initiated innovation, either as expert (lead) users, as consumers or as part of networks and communities. Yet, this research tradition offers but a set of prescriptive models to explain innovation (e.g. open innovation) and is largely blind to broader social, cultural and political aspects. The extensive body of research draws strongly on Schumpeterian understandings of innovation and explains the relationships between users and producers in terms of economic rationality and the preferences of key influential actors. That is, both producers and innovative users are seen as agents seeking to capture economic value. The main contribution of this scholarship is thus embodied in procedural toolkits for managers, recommendations for organisational adaptation and other strategies aimed at harnessing the value of user innovations.

The positivist tradition of user innovation scholars can be laid in contrast with insights from critical theory, cultural studies and historical analyses. Some commentators locate the issue of increased collaboration in technology development, not exactly as a challenge to the *status quo*, but rather as manifestations of emerging configurations of labour at the epochal turn variously known as post-Fordism or post-industrial capitalism (Thrift, 2006; e.g. Castells, 2010b). Marxist scholars have, for instance, advanced the notion of a new value form attached to the collective intellectual, affective, creative and knowledge-oriented labour which is, by means of new managerial techniques and communication technologies, resourcefully extracted through capitalist forms of production (Lazzarato, 1996; see e.g. Hardt, 1999; Hardt and Negri, 2006).

Maurizio Lazzarato has proposed the notion of 'immaterial labor' involving activities that 'combine the results of various different types of work skill: intellectual skills, as regards the cultural-informational content; manual skills for the ability to combine creativity, imagination, and technical and manual labor; and entrepreneurial skills in the management of social relations and the structuring of that social cooperation of which they are a part' (Lazzarato, 1996, p. 3). In the Marxist reading, the value of the new forms of labour is assumed to be accrued through social cooperation and enabled not only by computer languages but by human languages, culture, ideas and knowledges.

Emerging ICTs and social media sites have also paved the way for different forms of (free) digital labour enacted by users who produce cultural and intellectual content which is profitably internalised by firms (such as social media platforms) through the deployment of new digital tools and technologies for coordination (Terranova, 2000; Fuchs, 2014; Söderberg, 2015). To cite Tiziana Terranova (2000, p. 34): 'The expansion of the Internet has given ideological and material support to contemporary trends toward increased flexibility of the workforce, continuous reskilling, freelance work, and the diffusion of practices such as 'supplementing' (bringing supplementary work home from the conventional office)'. These arguments run counter to the techno-utopian ideologies and emancipatory views (see Barbrook, 1998) and the conceptions of knowledge work within management theory. Instead, they problematise the new forms of collaborative production as a phenomenon that is deeply linked with the old contradictions of industrial societies.

Feminists and the turn to the user in STS

STS scholars turned their attention to the user in the 1980s and 1990s with the emergence of critiques to technological determinism, corporate innovation and the underrepresentation of women in technology development. These preoccupations provoked a research agenda aimed at bringing users to the fore as key agents in technological change and questioning established discourses of innovation (Oudshoorn and Pinch, 2003). While I expand on the STS-inspired theoretical framework for this study in the next chapter, some contributions are worth mentioning here.

At the forefront of the turn to users were feminist scholars who challenged male-dominated and gender-essentialist discourses and practices of technological development and led a shift of the focus of analysis from designers and engineers to the contexts and manifestations of labour in all their diversity (Suchman, 1993b, 2002a; Wajcman, 2010; Haraway, 2013). In their critique of corporate innovation in the US, Lucy Suchman and Libby Bishop (2000) argued that the prevailing discourses of innovation are rooted in rather incremental and conservative agendas of change that are disconnected from more organic, reflexive, culturally-imbued and localised forms of action (see also Suchman, 2002a).

Similarly, gender studies advanced a critique to what was referred to as the 'i-methodology', or the (often unconscious) practice by designers and engineers of employing self-referential models for representing users (Oudshoorn, Rommes and Stienstra, 2004). The i-methodology, it was argued, led to problems of gender *scripting* and the reproduction of biases towards the preferences of designers -for the most part, middle-class white men (Akrich, 1992b; Oudshoorn, Rommes and Stienstra, 2004; Breslin and Wadhwa, 2017). Problematising the gendered nature of technology development helped not only to address difficulties with the adoption of technology but also to uncover the reinforcement of gender stereotypes in the practice of design (Wajcman, 1991). This issue has been widely explored in a range of empirical studies including, for example, reproductive technologies, computers, cosmetic products and household technologies (Cowan, 1987; Cockburn, 1993; Oudshoorn, 2003; van Oost, 2003). This scholarship elicited critiques around the exclusion of women in technological development, but also crucially put the question of users' agency at the centre of an agenda of research theory and policy (Wajcman, 2010). As Oudshoorn and Pinch pointed out: 'A detailed understanding of how women as "end users" or "implicated actors" matter in technological development may provide information that will be useful in the empowerment of women or of spokespersons for them, such as social movements and consumer groups' (2003, p. 6).

Semioticians and discourse analysts proposed the notion of *configuring* or *scripting* the user in order to delve with the questions surrounding technology adoption. Steve Woolgar (1990) observed that designers produce ideals of users that are then embedded in technological artefacts, thereby *configuring* users and framing what they can and cannot do as they make sense of (or *read*[3]) said artefacts. Similarly, Akrich and Latour suggested that engineers and designers inscribe meaning into artefacts based on imagined views of potential users, which might be done deliberately or unintentionally (Akrich, 1992a; Akrich and Latour, 1992). As pointed out by feminist scholars, the features inscribed in artefacts by designers often replicate existing categories of race, class and gender. Indeed, central to actor-network theory (ANT) is the collapsing of the ontological distinction between the technical and the social. In this view, artefacts too are seen as *actants* capable of altering the social world, and therefore can be bestowed by designers with a script that serves as a tacit or explicit guide to users (Akrich, 1992a).

Contemporarily, the social shaping of technology (SST) programme established a critical inquiry of technology against linear models of innovation and with a focus on policy intervention (MacKenzie and Wajcman, 1985; Sørensen and Williams, 2002). The idea of social shaping became a coherent argument against technological determinism; it was reasoned that rather than following an 'inner logic' (e.g. technical or economic), every stage in the design, implementation and use of technologies is characterised by deliberate choices influenced by cultural and political as well as narrowly-technical factors (D. A. MacKenzie and Wajcman, 1985; Edge, 1988; Williams and Edge, 1996). Crucial to the implication of users is that SST posits designers and users as both contributing to the shaping of technology. Although early SST scholarship focused too strongly in the (upstream) stages of design and production of technology, further extensions to the framework corrected this problem by acknowledging that technology is also shaped at later stages, for example, during its marketisation, implementation and use (Mackay and Gillespie, 1992; Sørensen, 1994). Two key concepts in the vocabulary of social shaping are *appropriation* and *domestication*, which refer to the processes of social and symbolic meaning-making that occurs in the contexts of use: 'Nothing happens after the introduction of technology unless it somehow is put to work and given meaning; unless it is appropriated by social actors' (Sørensen, 2002, p. 21).

[3] Woolgar proposed the metaphor of machine as text, whereby users construct meaning about technologies in the same way a text can be read differently by different audiences (see also Grint and Woolgar, 1997).

The critical programme of STS has been crucial in advancing a nuanced theorisation of technological change and user-technology relationships by unveiling conceptual shortcomings, questioning the dominant rhetoric of innovation, and going beyond purely pragmatic approaches. Although a central aim of STS has been to intervene in public policy (Sørensen, 2002; Sørensen and Williams, 2002; Suchman and Bishop, 2000), design practice and HCI have also profited greatly from the turn to users in STS scholarship (Scacchi, 2004; Johnson *et al.*, 2014; Hyysalo and Johnson, 2015).

Participatory design

Participatory design (PD) has its roots in early experiments with community participation in architecture and planning in the US in the 1960s inspired in the civic and democratic agenda of social justice movements (Sanoff, 1999). The political motivation at the time was to include citizens in the decision making concerning public space which was seen as a means to come up with better designs while tackling social issues. Out of these efforts, a range of methods, design tools and games were developed for enabling participation in architectural and environmental design which then underpinned a vigorous interventionist agenda of design practice and research (Luck, 2018). The political ideals of the participatory design movement were also embraced outside the US and in other domains of design. During the 1970s and 1980s growing concerns about the displacement and deskilling of workers resulting from the rapid computerisation of industrial processes sparked attempts to include more diverse perspectives in the design and introduction of new technologies in the workplace (Kyng, 1988). In Europe, and notably in Scandinavia, the so-called 'industrial democracy movement' fostered a socialist labour reformation in the workplace (Gustavsen and Qvale, 2014). What later became known as the 'participatory design movement' or the 'Scandinavian approach' stirred a wave of academic research and experiments on the involvement of workers in the design of industrial technologies (Asaro, 2000). The rationale behind these movements was that 'since the existing technologies were presumably all being developed to satisfy the interests of their purchasers, the business owners, and hence to increase productivity, control, and efficiency, the only effective means of empowering workers in competitive industrial markets would be the creation of alternative technologies designed around workers' interests.' (Asaro, 2000, p. 267).

Research within the rubric of participatory design has produced methodologies and techniques for bridging the work of engineers with the empirical knowledge held by users and allow these two, otherwise separate, actors to meet in the middle. Various techniques and tools were devised to elicit thinking and deliberation about future use scenarios including mock-ups, prototypes, simulations and 'future workshops' (Kyng, 1988; Simonsen and Robertson, 2013). As observed by Kensing and Bloomberg (1998, p. 168), '[t]hree main issues have dominated the discourse in the PD literature: the politics of design, the nature of participation, and methods, tools and techniques for carrying out design projects'. Although not without critics (see e.g., Kraft and Bansler, 1994), participatory design has remained both a critical and an interventionist approach to technology design, development and use. Not only it sought to involve citizens and workers through the democratisation of the decision making in key areas of design, but it has importantly influenced the epistemic orientation of design practice (Schuler and Namioka, 1993; Suchman, 1993a; Korsgaard, Klokmose and Bødker, 2016; Luck, 2018).

Participatory design has inspired a wealth of scholarly work oriented to inform industrial practice and policy in Europe and the US (Greenbaum, 1991; Spinuzzi, 2002). Although the original aims of PD were linked with political concerns with democratic construction of public space and the asymmetries of power between experts and workers within the boundaries of firms, the purview of 'participatory design' as a term has grown to a much wider scope of research and sites of action. Late empirical research, for example, explores new milieus and political concerns such as innovation in the public sector (Dittrich, Eriksén and Hansson, 2002), implementation of infrastructures (Karasti and Baker, 2008), engagements with grassroots and civic collectives (Björgvinsson, Ehn and Hillgren, 2010), and issues of user exclusion and discrimination of vulnerable groups (Kam *et al.*, 2006; Ruland, Starren and Vatne, 2008; Björgvinsson, Ehn and Hillgren, 2012).

Today, participatory design is often conflated with notions such as collaborative design or co-creation and is also linked, albeit tangentially, with user-centred design. The scholarly work around PD has, for instance, led to the establishment of specialised journals around the themes of user participation and co-design of information technologies (Muller and Druin, 2002; Brown *et al.*, 2012; Simonsen and Robertson, 2013; Vines *et al.*, 2015). As described earlier, some of the tenets of PD have been influential to the field of Human-Computer Interaction[4] and have been explored in a diversity of emerging domains in ICTs. Some examples from the literature include health information systems (Balka, 2012; Braa and Sahay, 2012), industrial design (Brandt, Binder and Sanders, 2012), urban planning (Saad-Sulonen and Botero, 2008), making and crafting practices (Tanenbaum *et al.*, 2013) and web technologies (Hess *et al.*, 2013). PD as a field has also branched out conceptually through fruitful exchanges with other academic traditions such as infrastructure studies (Karasti and Syrjänen, 2004; Le Dantec and DiSalvo, 2013; Karasti, 2014), feminist studies (Suchman, 2002a), cultural studies (Muller and Druin, 2002), and Science and Technology Studies (Callon, 2004; Ehn *et al.*, 2014), to name a few. In this thesis, I draw on some of the concepts from authors ascribed to the 'school' of participatory design.

User-centred design

The language of 'users' has been omnipresent, particularly in the vernacular of ICT researchers and practitioners, often accompanying a strong insistence on the need to centre design and development around (or *configure*) users through methods such as user research and usability tests (Woolgar, 1990). Scholars working in the spheres of design theory and practice have taken a focal interest in users since the dawn of computing. The interdisciplinary field of Human-Computer Interaction (HCI) has at the forefront of researching users and their adoption of new computing technologies.

Indeed, HCI arose as a response to the challenges of introducing computers in organisations and the mass adoption of personal computers during the 1970s and 1980s (Norman and Kirakowski, 2017). The HCI community subsumes a wide breadth of disciplines including design, psychology, ergonomics and the social sciences (Dix, 2017). While the agenda of HCI originally focused on matters of computers' usability and user interfacing, it has evolved along with the advances in information technologies producing an extensive body of research throughout the last decades and a vigorous programme of conferences and journal publications. New research in HCI

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[4] Indeed, authors ascribed to the participatory design also take part in HCI publications and conferences as well as in Computer Supported Cooperative Work (CSCW). The field of CSCW is part of a wider socially oriented tradition in systems design. Although CSCW is also focused in workplace contexts, it has a stronger focus of the design of 'groupware' or technologies for collaboration (see Schmidt and Bannon, 1992)

seems to be up to date with the state of the art, covering new developments on mobile and wearable devices, sensors, adaptive systems, social networks and social media, virtual environments, games, and more recently digital fabrication, cloud computing, internet of things, artificial intelligence and machine learning (Phipps, 2013; Dix, 2017; Norman and Kirakowski, 2017).

The notion of 'user-centred design' (UCD) was introduced in the 1980s (Norman and Draper, 1986) and has been a hallmark of HCI. User-centred design grew out of the need to fill in the gaps in the knowledge held by designers about users. To address this problem, it was deemed necessary to go beyond simply building psychological models of users, and to broaden the empirical scope of design onto other aspects such social relationships or the organisation of work (Bannon, 1986). Principles of UCD have been widely applied to the design and development of computer-based systems such as software products, websites, applications, automated systems, mobile telephones and digital television (ISO, 2019). Various techniques and methods can be attributed to the notion of user-centred design, for example: devising user scenarios and personas which are used at various stages of systems' design and throughout their lifecycle (Lior, 2013).

Participatory design methods and feminist critiques of technology have been influential in HCI. As a result, speculative work, comprising interventionist and ethnographic approaches, has been proposed as a means to arrive at richer understandings of the contexts of technology 'in the wild' and gather sociological insights that could prove useful for designers (Button, 2000). Some of the concepts and techniques developed within UCD suggest, at least to an extent, a degree of interactive engagement with users, even if only as information providers (Chow, 2013). Contextual design, for example, is an attempt to gathering rich situated user knowledge (Holtzblatt and Beyer, 2017). Still, as opposed to democratic-oriented movements such as participatory design, UCD remains being a call for gathering rich accounts of users and their contexts of use both to inform the practice design and to understand the interaction between users and technology (Fallman, 2003).

Although HCI has brought users to the fore by eliciting important questions of agency and identity, it falls short of challenging underlying assumptions about innovation. Indeed, the idea of user-centred design is, by definition, fully embedded in a rather binary understanding of designers and users (or consumers). This issue is rooted in an almost exclusive preoccupation with the settings of use and interaction as the prime sources of knowledge for design while being blind to the uncertainty of future users or the possibility of resisting/rejecting users (Wyatt, 2003). Criticism has come from within the HCI community. Don Norman, the founding father of user-centred design, has more recently denounced the approach for its inadequacy in delivering radical innovations: 'Although the deep and rich study of people's lives is useful for incremental innovation, history shows that this is not how the brilliant, earth-shattering, revolutionary innovations come about. Major innovation comes from technologists who have little understanding of all this research stuff: They invent because they are inventors.' (Norman, 2010, p. 2). Gilbert Cockton (2012) has also challenged the lack of justification underpinning UCD, arguing that it has led to an almost fundamentalist fixation with user-centredness and advocating for more integrative and multidimensional strategies for design.

STS scholars have also been concerned with the idea of user-centredness. Steve Woolgar, for one, has forewarned about the limitations of *configuring the user* -or the process of meaning-making by developers: 'Insiders know the machine, whereas users have a configured relationship to it, such that only certain forms of access/use are encouraged. This never guarantees that some users will not find unexpected and uninvited uses for the machine. But such behaviour will be categorised as bizarre, foreign, perhaps typical of mere users.' (Woolgar, 1990, p. 89). Similarly, user-centred design could lead to short-sightedness and engender a 'design fallacy' (Stewart and Williams, 2005). To be clear, a preoccupation in gathering knowledge about users may cause designers to overlook other important factors, such as the possibilities for modifications during use, the interests of other stakeholders, the economic incentives for standardisation, and the role of existing infrastructures (D. A. MacKenzie and Wajcman, 1985; Procter and Williams, 1996; Williams, Stewart and Slack, 2005). Studies of enterprise software, for example, have revealed that a 'generification' of software packages, which is based on a rather agnostic attitude towards particular user requirements, could lead to successful technology adoption across different user domains (Pollock and Williams, 2009; Pollock, Williams and D'Adderio, 2016).

Networks of innovation in Information Systems research

Finally, I would like to include in this review the work on innovation arising from the scholarly field of Information Systems (IS). Albeit not directly concerned with problematising users, IS has produced a remarkable body of research that deals with the emerging distributed aspect of innovation in information and communication technologies. While early IS research in the 1980s focused largely on information technology within single vertically-integrated organisations (Sidorova *et al.*, 2008), recent studies have explored contexts of heterogeneous networks with attention to different forms of innovation (e.g. technical organisational, processual).

Some empirical studies in this vein have to some extent argued against linear models (Swanson, 1994; e.g. Fulk and DeSanctis, 1995) and explain innovation with a metaphor of networks with the aim to capture the distributed, chaotic and dynamic nature of the process (Tuomi, 2006; Boland, Lyytinen and Yoo, 2007; Van de Ven, 2017). A number of IS scholars speak of 'digital innovation' drawing heavily on a Schumpeterian perspective whereby entrepreneurial actors and organisations are able to innovate by combining digital and physical components in novel ways (Yoo, Henfridsson and Lyytinen, 2010; Yoo *et al.*, 2012). A premise of this branch of IS research is that so-called digital technologies have engendered new ways of collaboration, business organisation and involvement of dispersed users and communities. The focus on innovation within IS has brought about a great deal of cross-pollination with management studies (Yoo, 2012).

The IS tradition has a strong focus on the materiality of technology and its implications in transforming the innovation processes. To cite Yoo et al. (2010, p. 734): 'We now create digitized products with loose couplings across devices, networks, services, and contents in an irrevocable way. Thus far, we have only seen the early forms of such digitized products and therefore can only dimly observe the forms of the emerging organizing logic of digital innovation'. To these authors, the distinct technical qualities of digital technology and the increasing pervasiveness of networks are thought to lead to an enduring effect in the way innovation is conducted.

More recently, authors have taken a step towards establishing a broader 'socio-material' school (Orlikowski and Scott, 2008). This theoretical work deals with the emerging organisational and technical complexities brought about by widespread digitisation. The unique nature of digital artefacts, for instance, has been scrutinised to understand the distinct ways in which they are appropriated, edited, and distributed in contrast to physical (non-digital) objects (Ekbia, 2009; Kallinikos, Aaltonen and Marton, 2010; Kallinikos *et al.*, 2013). The ontological ambivalence of digital artefacts, it has been argued, allows developers to manipulate and expand their capabilities in myriad new ways thereby making new business models and technical arrangements possible (Kallinikos, Aaltonen and Marton, 2010; Kallinikos *et al.*, 2013).

Authors in the field of IS frequently invoke the concept of generativity –or the potential for technology to enable further independent configurations which are contingent to the context– as a heuristic for explaining innovation in information systems (Henfridsson and Bygstad, 2013; see also Chapter 3). Mobile platforms, for instance, have been exemplified as generative insofar as their affiliated developers leverage the physical and logical interfaces being made available to them, under the rules of the platform owners, to create new applications (Constantinides, Henfridsson and Parker, 2018). Similarly, in the case of hardware, artefacts which offer interfaces and options for reconfiguration would be seen as more generative than those which are black-boxed or designed for specific functionalities. To a large extent, consumer products are delivered as black boxes with little room for repurposing or reconfiguration (Nielsen and Hanseth, 2010). Generative artefacts, on the contrary, are purposely designed to be programmable and combinable with other elements. These products may primarily be targeted to developers who leverage the configurability for building prototypes and applications.

In much the same way, the turn to modularity in the development of information technology has been a key theoretical consideration for IS scholarship (c.f. Baldwin and Clark, 2000). The generativity approach has been widely used to explore the increasingly complex relationships between firms and users in the context of the digital economy and data-oriented business models. In recent years, IS scholars have elicited timely enquiries at the intersection of digital platforms and infrastructures and offer a new vocabulary and concepts (Gawer, 2014; see e.g. Altman and Tushman, 2017; Constantinides, Henfridsson and Parker, 2018; Hanseth and Bygstad, 2018). Empirical work around emerging platform ecosystems and digital infrastructures have taken a central place in the IS research agenda with the aim of problematising innovation in the context of widespread digitisation (Tilson, Lyytinen and Sørensen, 2010; Parker, Van Alstyne and Jiang, 2017; McIntyre, Srinivasan and Chintakananda, 2020). The so-called ‘platformisation’ of systems and the economy has been recently problematised to make sense of the new data-oriented forms of innovation (Constantinides, Henfridsson and Parker, 2018; Hanseth and Bygstad, 2018; Cennamo and Santaló, 2019).

Table 1: Different research perspectives on user involvement in technology production

	Research agenda	Research tradition/methods	Conceptual contributions
Management theory	Strategic management and innovation theory	Economics of innovation, case studies, surveys	User-dominated innovation User innovation and Lead-user (von Hippel, 1986; Lüthje, 2004; Baldwin, Hienerth and von Hippel, 2006)
Critical theory and cultural studies	Critique of labour, power and the status quo	Marxism, political economy, social theory	Immaterial labour, digital labour, digital economy (Lazzarato, 1996; Terranova, 2000; Söderberg, 2015)
Participatory Design	Workers, civil society and community participation in design. Politics of design	Action research, design theory and practice, experiments	Artful integration Collaborative design principles and practices (Schuler and Namioka, 1993; Suchman, 2002a; Ehn, 2008)
Human-Computer Interaction	Research-oriented Design Design-oriented research, computing interfacing	Ethnography, user-research, consumer research	User-centred design Contextual design (Norman and Draper, 1986; Holtzblatt and Beyer, 2017)
Science and Technology Studies	Critique of technology and policy intervention	Semiotics Discourse analysis Feminist epistemologies Ethnography	Interpretive flexibility Domestication Scripting/configuring the user (Bijker, Hughes and Pinch, 1987; Fleck, 1988; Akrich, 1992b; Akrich and Latour, 1992; Sørensen, 1994; Williams and Edge, 1996; Wyatt, 2003; Oudshoorn, Rommes and Stienstra, 2004)
Information Systems	Information systems development, Innovation in digital platforms and infrastructure	Organisation studies Information infrastructure	Network innovation, platform ecosystems (Tuomi, 2006; Yoo, Lyytinen and Jr, 2008; Constantinides, Henfridsson and Parker, 2018)

Tracing practices and cultures of user involvement in information technology

In this section, I review some historical markers of collaborative technology development that have inspired contemporary practices particularly in the contexts investigated in this thesis. Looking back at the history of the internet one encounters myriad examples of collaborative modes of work in the realms of infrastructure, hardware and software. To arrive at the contemporary scene of collaborative work in the internet of things it seems crucial to look back particularly at three cognate contexts: free and open source software, hardware hacking and community informatics. The experiences of these movements are of relevance here not only as empirical points of reference for the analysis but because of their implications to the sites of enquiry in this thesis in terms of practices, membership and strategies of organisation and governance.

The principles of open source have increasingly been mainstreamed becoming a hallmark of today's software development both at the level of communities and amateur developers and in the corporate world. More recently, some of these ideas have been translated into the realm of hardware development as an attempt to facilitate the free sharing of hardware designs and facilitating collaboration in the production of physical artefacts and infrastructure. Finally, community networks have for decades been exemplar models of self-organised telecommunication infrastructure deployment. Even today they remain a legitimate technical and organisational alternative, not only to the lack of internet access in underserved areas but to the dominance of large internet service providers.

Free and Open Source Software

Much has been written about the origins, economics, culture and ethics of free and open source software (FOSS). Over the years, this model of collaborative development has permeated areas beyond the original strongholds of the hacker culture. What started as a political response to the commodification of software with the Free Software Foundation led by Richard Stallman, later became common practice across the software industry. The free software movement is predicated on the dictum of granting users freedom to run, study, modify and distribute software, or what was described by Stallman as the 'four essential freedoms' (Stallman, 2013). These freedoms were codified in the GNU Public Licence (GPL) which constituted an instrument for the self-propagation of free software that sought, in an ironic way, to exploit the copyright law by reversing it. The term *copyleft,* as coined by Stallman, captures this idea: 'our aim is to give *all* users the freedom to redistribute and change GNU software. If middlemen could strip off the freedom, our code might "have many users," but it would not give them freedom. So instead of putting GNU software in the public domain, we "copyleft" it. Copyleft says that anyone who redistributes the software, with or without changes, must pass along the freedom to further copy and change it. Copyleft guarantees that every user has freedom.' (Stallman, Richard, 2001 emphasis in original).

Under the rules of GPL, even modified versions of free software ought to be distributed with free (public) access to the source code, which is a requirement of the aforementioned four essential freedoms. Although the GPL license does not inherently impede commercialisation, it limits privatisation and free-riding by fostering a culture of voluntarist collaboration and sharing. In other words, companies would have a disincentive to privatise free software in that they would thereby miss out on the potential for continuous improvements by a crowd of developers. An underlying assumption of free software is that a crowd of independent developers cooperating on a common software project leads to better and faster results than those produced by a team of in-house developers. As illustrated in Eric Raymond's maxim (1997), 'given enough eyeballs, all bugs are shallow'.

As much as the tenets of free software opposed the privatisation of software, they were not at odds with commercial endeavours: advocates of free software engaged in the sales of physical copies of software and other complementary lines of business such as customisation and support services. However, internal ideological schisms about the stance of the movement in regard to the involvement of corporate actors eventually gave way to the notion of open source software. The new label removed the ambiguity of the word 'free' and although it fostered the unrestricted distribution and modification of source code, it also provided concessions for the privatisation of software derivatives making the notion of open source attractive for technology firms (Söderberg, 2015). Open source software emerged as a pragmatic compromise between openness and commercial interests and, despite the political differences, the two camps are commonly conflated in the literature. Among the most commercially successful open source software projects are the Linux operative system, the Mozilla web browser and Apache, the most widely used web server (Bretthauer, 2001). In the last decades, open source software has become a mainstream model of development as proprietary software companies such as IBM and Microsoft have adopted open source principles on the grounds of efficiency and gaining competitive advantage (Landau, 2010). More recently, the development processes of open source software have been increasingly converging or deployed in tandem with agile methods commonly used in the development of proprietary software (Sahraoui, Al-Nahas and Suleiman, 2012).

The implausibility of an alternative model of technology development being commercially successful in spite of the hegemonic regimes of intellectual property has since the outset been a source of intrigue, particularly for economists. Various commentators have searched for explanations in the uncanny economic dynamics of information-based products brought about by the advent of the internet. In *The Wealth of Networks* Yochai Benkler argues that the emergence of a 'networked information economy' gives way to new collaborative and decentralised interactions that seem to escape the logic of markets (Benkler, 2006). In his view, the immateriality of software along with the wide accessibility of the internet allows for inexpensive and fast exchange and replication of the source code. This engenders a situation of low costs and big gains for users and developers that is comparably more efficient than the privatisation of software. For liberal economists, the fact that adherents to free and open source software do not inherently seek to privatise information goods, while still being motivated to produce it, characterises a sort of 'gift economy' (Bergquist and Ljungberg, 2001; Weber, 2004). In a gift economy, they would argue, the efforts of contributors are motivated by collaboration as much as by competition, with contributors striving for self-expression, reputation and prestige among their peers. The so-called peer to peer (P2P) movement has been a longstanding model of production associated with FOSS which advocates for outflanking hierarchies and intermediaries through decentralised and self-organised forms of production (Moore, 2011). Through leveraging free and open source software, P2P production promotes alternative forms of exchange through the internet and the possibility for 'digital commons'.

From the perspective of the economics of innovation, Lawrence Lessig (2001) has argued that the privatisation of information goods via intellectual property represents as a hurdle, rather than an incentive, to creativity and innovation in an economy of information. The benefits that arise out of these collaborative interactions are frequently registered in terms such as ‘the public domain’, ‘the commons’ or ‘positive network externalities’. Yet, as pointed out earlier in this chapter, the value of users’ creative acumen may also be variously appropriated by firms. Marxist authors would for instance argue that the privatisation of the collective production such as open source software is but a manifestation of ever more subtle forms of exploitation (Terranova, 2000; Söderberg, 2015). In his critique of FOSS Johan Söderberg argues that ‘the employment of user communities by companies is part of a more general trend where audiences and consumers become sources of surplus value for capital’ (2015, p. 50). The model of FOSS development, Söderberg suggests, ‘is neither a market nor a firm, but might be characterised as a network’ (2015, p. 137). These observations point to the ambivalence of FOSS when it comes to markets and conceptions of private property: while it competes with proprietary software leveraging its efficiency in terms of productivity and development costs, it relies on the free diffusion of information among its contributors which conflicts with the idea of exclusion through scarcity.

The FOSS model has inspired initiatives in other areas of information production. Similar principles, organisation of work and legal instruments are deployed not only to foster innovation but to safeguard common information goods from privatisation. Open source schemes and experiments have been tried out in different domains of knowledge and technoscientific production where intellectual property has also been viewed as posing a barrier rather than an incentive to innovation (Hope, 2008). Biotechnology is a salient example where models inspired by open source have been developed in the areas of health, pharmacology and agriculture (Maurer, Rai and Sali, 2004; Hope, 2008; Nicolosi and Ruivenkamp, 2013; Deibel, 2014). Creative Commons, a non-profit founded by Laurence Lessig in 2001, is perhaps one of the most noteworthy initiatives inspired by open source. Creative Commons licences seek to replicate, at least to some extent, the principles of the GPL licence in the production of cultural content including music, photography, film, scientific publications, among others.

The recasting of the open source principles into other domains of copyrightable content has sparked high hopes and new buzzwords such as 'free culture' (Lessig, 2001), yet is not without shortcomings. A study of the open filmmaking movement, for instance, showed that the model failed to live up to its high expectations due to internal disputes among its proponents and difficulties in establishing a viable business model (Giannatou *et al.*, 2019). Another such attempt is also observed in the realm of physical artefacts with the 'open-sourcing' of hardware, or more precisely, the instructions and blueprints behind its construction. The history of the involvement of users in the production of hardware, however, pre-dates that of FOSS and can be traced back to early techno-cultures of ham radio operators and explorations with microcontrollers.

Hardware hacking and open hardware

In her book *Ham Radio's Technical Culture*, Kristen Haring (2007) provides a comprehensive account of radio amateurs (most of them white men) in mid-twentieth-century US and Canada, who engaged in the practices of crafting, repairing, testing and repurposing radio equipment, a popular leisure activity that is still widely practised today. Later, in the early days of computing, the advances in microcontrollers offered an opportunity for people within and outside academia to tinker with hardware. The term 'hacking' was coined around this time, which alluded to the collegial practices of mutual recognition and competition around creative work with electronics within labs of the Massachusetts Institute for Technology (MIT) (Levy, 2010).

In Steven Levy's account, the *hacker ethic* 'was a philosophy of sharing, openness, decentralization, and getting your hands on machines at any cost to improve the machines and to improve the world' (2010, p. ix). In the 1970s, predating the arrival of the personal computer, the Homebrew Computer Club was an informal group of hackers, engineers and computer enthusiasts in Silicon Valley which paved the way for the development of the Apple computer (Levy, 2010). This period was marked by the popularisation of magazines such as 'Popular Electronics' oriented to a readership of hobbyists and enthusiasts with an interest in DIY projects with microelectronics and programmable devices. Countercultural practices such as the Steampunk aesthetic in the 1980s were also outstanding markers linked with a popular appropriation of hardware (Onion, 2008).

These early techno cultures map onto contemporary techno-utopian idealisations such as the ‘maker culture’ shaped largely by publications such as Maker magazine (Sivek, 2011), but also in the landscape of grassroots communities of hackers organised in hackerspaces around the world, and a growing market of low-cost DIY electronics. The recent proliferation of hardware development platforms such as Arduino, Raspberry Pi and the BBC Micro Bit has sparked an interest in hardware programming[5] used not only within the hacker and hobby-oriented circles but in computer literacy programmes, and the production of scientific equipment and industrial applications (Buechley and Hill, 2009; Hertz, 2011; Pearce, 2016; Schmidt, 2016).

As mentioned above, more recently there have been efforts to translate the principles of FOSS into the realm of hardware. The landscape of open source hardware (OSHW) initiatives (also known as open hardware) is highly diverse with stakeholders from the industry as well as from hacker communities who seem to coincide in various definitions and principles (OSHWA, 2012). In a broad sense, the impetus behind open source hardware initiatives is centred on the open generation of the information components needed for the fabrication of hardware (e.g. designs of printed circuit boards (PCBs), schematics, instructions, diagrams). In an analogous process to software development, the production of PCBs entails the transformation of hardware designs into a set of codified instructions for arranging electronic components and the printing of circuits with the aid of electronic design automation (EDA) software. A commitment to open source hardware would thus involve a release of the necessary information to replicate a given piece of hardware.

Yet, compared with FOSS, OSHW is faced with a range of additional complications. For one, hardware development involves a series of steps with manifold information inputs including not only detailed layouts, but also lists of materials, firmware and detailed documentation. Each of these inputs is not homogeneously covered by intellectual property laws. Source code and designs in open hardware, for instance, rely on open source licences and copyright, while physical objects are covered by

[5] Many of these platforms are in fact software-programmable with modularised (not hardwired hardware) elements such as radio interfaces

patents. These asymmetries have resulted in uneven degrees of openness and commitments within the open hardware community (Ackerman, 2008).

A perhaps more crucial complication is the high costs of development. While the cost of replication and distribution of open source software is marginal, open hardware demands significant upfront costs for prototyping, iterating and scaling up. To tackle the issue of scalability, open hardware initiatives are predicated in a trend of dropping costs of components and flexible processes of the development that rely less on hardware modification (OSHWA, 2012). For instance, low-cost generic hardware for prototyping and programmable chips such as FPGA (field-programmable gate array) reduce the complexity of development by allowing for multiple configurations and making the process more reliant on software. Still, the target audience of OSHW might be restricted to small scale experimental projects or to actors relying on economies of scale to keep marginal costs down (Powell, 2012).

In recent years, open hardware has gained a renewed thrust with the advent of the internet of things. The development of new IoT devices and the rollout of low-cost network infrastructure have been facilitated by the adoption of generic hardware platforms and modules. The use of 'software-defined hardware', for instance, has been widely used for low-cost experimentation by amateur as well as professional developers in domains as diverse as sensing infrastructure, environmental monitoring or scientific equipment (Fisher *et al.*, 2015; Pearce, 2016). In the context of this study, open hardware development platforms such as Arduino and a range of sensors and modules constitute essential building blocks used by user communities and professional product developers.

Community informatics and wireless community networks

The idea of community informatics can be traced back to the 1970s and has its roots in a strong belief by social activists in the US -mainly computer professionals and hobbyists- in the power of information technologies to improve the living conditions of communities (Schuler, 1996; Carroll and Rosson, 2003). Community informatics advocates promoted an approach of civic and inclusive design and management of information systems and networks aimed at empowering communities and addressing social issues at the local level (Carroll and Rosson, 2007; Gurstein, 2007). Community networks were established to address infrastructural gaps, improve local business activity, enable political action and tackle societal problems such as homelessness and access to education in remote areas (Rogers, Collins-Jarvis and Schmitz, 1994; Unchapher, 2002). These early conceptions of community networks leveraged existing networking and computing technologies and their tools evolved alongside the development of the internet from early protocols to the World Wide Web (Carroll and Rosson, 2003).

The spirit of early community informatics is still present in contemporary community efforts to empower citizens with ICTs which have spawned around the world, including the Global South. In an article titled *Wireless Community Networks*, Saurabh and Agrawal (2003) sketched an example of a low-cost wireless topology as a solution to provide internet access to rural areas based on the then-new IEEE 802.11 (Wi-Fi) standard. Throughout the 2000s, the IEEE 802.11 wireless standard, which could operate in a free-to-use spectrum band, became widely adopted in the computer industry and underwent several improvements in terms of speed and range. In parallel to these developments, the existing proposals of community networks evolved to more sophisticated and robust mesh topologies (Frangoudis, Polyzos and Kemerlis, 2011). In the last two decades, numerous cases of wireless community networks have been documented in scientific publications evidencing the diversity of models of self-organised telecommunications infrastructure across the world. During this time, there has been an intensified effort on developing the technical, economic and organisational aspects of grassroots wireless community networks (Szabó, Farkas and Horváth, 2008).

Wireless community networks are generally underfunded, depend on the work of volunteers and thus struggle to scale up and attain sustainable sources of funding for their operation. Furthermore, modern broadband technologies require high infrastructural investments which pose a challenge to this type of self-organised initiatives. Still, there are examples where community-owned infrastructures have succeeded in achieving a sustainable model even when operating directly in competition with incumbent telecom service providers. As of January 2019, the Institute for Local Self Reliance listed 800 community networks across the U.S., including municipal and cooperative networks (ILSR, 2019). In other geographies, some emblematic examples include guifi.net in Catalunya, Freifunk in Germany, Ninux in Italy, AWMN in Greece, FunkFeuer in Austria, Wireless Antwerpen, Wireless

Leiden, Bogotá Mesh and Monte Video Libre (Lawrence *et al.*, 2007; van Oost, Verhaegh and Oudshoorn, 2009; Baig *et al.*, 2015). These grassroots organisations provide not only access to the internet via broadband sharing, but also enable local and self-reliant telecommunication infrastructure and networking services which are governed in a bottom-up fashion.

Much of the recent work on wireless community networks delves with developing technically-sound deployments and is often authored by project managers and community members, covering topics such as network architectures, traffic modelling, communication protocols and anecdotal evidence on the viability and performance of network implementations (e.g. Maccari and Lo Cigno, 2015). Some research projects have reported on the politics, economics, sustainability and legal issues of contemporary community networks, with a normative agenda aimed at informing policy to support community network initiatives (Giovanella, 2016; Micholia *et al.*, 2018). Some noteworthy studies have explored community networks from the perspective of innovation studies, Science and Technology Studies and social theory (Söderberg, 2010, 2011; Verhaegh, 2010; Verhaegh, Oost and Oudshoorn, 2016). The research on community networks stands somewhat in the fringes of the enquiries on technology production and innovation. Yet, it sheds light on important issues of sustainability, tackling digital divides (for example between the North and the South) and technology ownership and sovereignty. In contrast to the vocabulary of consumers, users and developers from the mainstream of innovation studies, the study of contemporary community networks[6] proposes new concepts such as grassroots and civic innovation and technological commons.

Converging collaborative practices in the internet of things

As a corollary to this review, I shall discuss how both formalised and counter-mainstream collaborative practices in the areas of software, hardware and wireless networks bear on the contemporary landscape of the internet of things (IoT). To do this, I unpack the significance of the IoT and assess how this emerging technological

[6] While the term 'community network' was previously used in the sociological sense to refer to communities making use of communication technologies for social organisation (Smith and Kollock, 2002; see e.g. John M. Carroll, 2014), its more recent use in the literature generally alludes to the distinct organisational and technical features of grassroots and community-operated telecommunication networks

paradigm is being shaped not only by industry and regulatory actors but by the experience of past collaborative efforts.

The internet of things is a moving target: there is no unified definition and it coexists with several, perhaps less prominent, variants such as ubiquitous computing and ambient intelligence and with new labels such as cyber-physical systems and edge computing. Despite its vagueness, the term is now widespread in the industry as well as in high-level policy documents and future-oriented discourse revolving around visions of automation, prediction and pervasive digitisation. The internet of things has prevailed as an effective marketing term and has a track of hyped and optimistic forecasts from researchers and commentators many of which draw heavily on projections by industry analysts of the number of objects getting connected to the internet (Evans, 2011; see Atzori, Iera and Morabito, 2014; Gartner, 2015; Avital *et al.*, 2019).

Taking a closer look at the internet of things one encounters a complex and heterogenous world inhabited by myriad actors including suppliers, standard organisations, platforms, regulators, developers and users. IoT applications demand the integration and interoperability of various disparate systems and the coordination of actors working in different domains of expertise such as software programming, computer science, network engineering and hardware design. As a result, a great deal of IoT applications and services are *bespoke*, based on specific requirements and exigencies of automation or monitoring projects.

Instantiations of the IoT are frequently associated with the idea of 'smartness'. Industry actors widely use the descriptor 'smart' to highlight the automation-oriented properties of IoT technological offerings (e.g. smart home, smart agriculture, smart grids, smart cities). Although a wealth of smart devices such as wearables, trackers and smart meters are available in the market, there are seldom coherent 'packaged' solutions for many of the envisioned applications of the internet of things. Instead, most smart solutions demand strenuous work of integration and coupling of different building blocks such as sensors, networks, security protocols, data routing and storage, analytics and graphic interfaces. Such a complex value chain paired with the applicability of IoT in many domains or verticals has resulted in a highly complex and fragmented landscape.

Despite the fact that the internet of things evokes a highly industry-led battleground, non-corporate actors (including users) have been recognised as crucial agents in the formulation of industry roadmaps and future-oriented policy. Much of the top-level discussion revolves around the need for inclusivity, user-centredness, meaningfulness, tackling digital divides and fostering business opportunities in markets as diverse as consumer products, supply chains, agriculture or large-scale smart city solutions (see Atzori, Iera and Morabito, 2010; Frolund *et al.*, 2014; Kranenburg *et al.*, 2014; Lindtner, Greenspan and Li, 2015). However, beyond consultations, market research and a focus on user-centred design, the view from industry and policymakers is still largely blind to the possibility of bottom-up forms of involvement in innovation.

While largely ignored in policy debates, bottom-up and alternative modes of production have not remained stagnant and are not strange to the world of the IoT. Much of the existing technical and organisational knowledge from previous grassroots movements and modes of collaboration in fact seem to have found a common place in the IoT. Indeed, many of the social formations and practices of previous collaborative efforts in open source software, hardware hacking and community networks are still relevant today and have a direct bearing on the production of internet of things networks and applications.

This thesis draws attention to just such emerging spaces of action located under the broad banner of IoT. As I will demonstrate in the empirical chapters, there are continuities that stem from the aforementioned alternative practices and cultures. IoT practitioners build strongly on the principles of open source as the *de facto* mode of collaboration and distribution of software. More so, the open source ethos has not only been streamlined into development practices, vocabularies and protocols of collaboration with dispersed groups, but it has also been deployed in the generation of legal structures and community statutes. The development of physical devices is similarly a practice that is carried out both by established vendors and new entrants through the use of generic development tools (e.g. modules, sensors and open hardware) and various approaches to manufacturing. Finally, some existing community network initiatives have ventured into the world of internet of things, bringing along their organisational and technical stocks of knowledge and reworking their strategies in light of the new conditions. Community-led deployments of IoT networks resemble, to some extent, the organisational and governance structures of wireless community networks as they are inspired by or carried out by members of community networks.

Conclusion

In this chapter, I have sought to distil the broad notion of user involvement in ICT production both as a line of enquiry within different academic disciplines and as a quality of past and current techno-cultures and movements that are now brought to bear in the empirical context of this thesis. I have recounted how different academic disciplines have looked at users and highlighted their contributions and relative shortcomings. The theme of user involvement in innovation has been a remarkable site of contention in scholarly research and design practice judging by the diversity of epistemic angles and political agendas. The fields of management and information systems have taken a pragmatic stance with a focus on producing prescriptive models and toolkits for managers and system developers to grapple with emerging forms of innovation. These models, albeit blind to non-market forms of labour, are not removed from broader readings of the global political economy that locate the phenomenon within a paradigm shift marked by a revolution in information technologies (Castells, 2010a).

User involvement in innovation has also been a site of critical enquiry within STS. Building on feminist critiques of dominant discourses and practices of innovation, STS scholars have advanced a nuanced problematisation of user-technology relationships and a strong theoretical and policy-oriented agenda. Lastly, it seems equally relevant to look at the practice-oriented fields of human-computer interaction and participatory design. HCI is of salience here due to its lasting preoccupation with gathering increasingly detailed understandings of users to inform design. Conversely, owing to its roots in political activism, participatory design has taken a more interventionist approach and has elicited important questions of agency, inclusivity and democracy.

In the second part of this chapter, I have reviewed three emblematic bottom-up movements and cultures of collaborative technology development that serve as empirical references to the emerging non-conventional sites of action in the realm of the internet of things. The experiences, business models, alliances, vocabularies and social structures wrought as a result of these movements are illuminating (if not instrumental) for the current collaborative developments and the new forms of user involvement within the IoT landscape. These forms of user involvement lie at the centre of this study and call for critical scrutiny of the diversity of work practices from various flanks. In this thesis, I take an interest not only in the collaborative creation of discrete artefacts or pieces of software in the realm of the IoT, but also in the seeming convergence and coupling of practices across the domains of hardware, software and infrastructure. To make sense of this phenomenon, I propose a bottom up exploration informed by a critical assessment of users. In the next two chapters, I will outline a theoretical framework inspired in Science and Technology Studies and delineate the research design used for this thesis.

Chapter 3 – Towards an ecological analysis of the internet of things

Introduction

Discourses of innovation have long been embedded in grand narratives of progress. Schumpeterian and neo-Schumpeterian economics have been particularly influential in articulating theories of economic development underpinned by technological innovation and the prowess of inventors, applied scientists and entrepreneurs. These world views have importantly informed policy, strategic management, and the methods of production of artefacts and systems in Western economies. Yet, at the same time, the prevalent discourses of innovation have been strikingly detached from the contexts where technologies are used and also possibly modified, repurposed, rejected or resisted.

Outside the labs, factories and other institutions of technology production, such a divide has been concretised in mismatches, inequalities and contradictions in the way artefacts are deployed and used - as feminist scholars have amply demonstrated (Cockburn, 1993; Oudshoorn, Rommes and Stienstra, 2004; Wajcman, 2010). Reflecting on the work of system designers in the corporate world, Lucy Suchman observed that ‘a consequence of the prevalence of the *view from nowhere* within professional design is that designers are effectively encouraged to be ignorant of their own positions within the social relations that comprise technical systems, to view technologies as objects and themselves as their creators’ (Suchman, 2002a, p. 95 emphasis added).

Against this backdrop, the call from critical scholars has been to place the rhetoric and politics of innovation under scrutiny and interrogate the practices surrounding the production and use of artefacts (Star, 1990; Sørensen and Williams, 2002; Suchman, 2002a; Jasanoff, 2004; Haraway, 2013). To do this, anthropology has offered invaluable tools to access the local and everyday work practices that are largely underplayed in innovation discourses and that might go unnoticed within the spheres of technology production.

In this chapter, I delineate the theoretical framework that underpins the empirical and analytical work of this study. As a point of departure, I delve into the social-constructivist tradition within science and technology studies. In particular, I discuss three broad schools of thought, namely 'social construction of technology' (SCOT), 'actor-network theory' (ANT) and 'social shaping of technology' (SST). These theories of technology and society have grown out of a shared critique of 'linear' innovation models and essentialist understandings of technological change. They are closely related and maintain a high level of conceptual overlap. I trace the intellectual origins of these approaches and touch on some of the concepts and methods which are applied in this thesis.

In particular, I draw on the social learning perspective on the study of innovation (Sørensen, 1996) and articulate an understanding of technological change as iterative, incremental and collaborative. The framework offers a means to explain the patterns of evolution in the empirical contexts of this study by looking at how adjustments have been made as a result of ongoing trial and error. Next, in light of the complexity of studying the internet of things empirically, I turn to studies of infrastructure. Drawing on vocabulary and concepts from this scholarship, I delineate an analytical strategy to grapple with infrastructure-like technologies spanning multiple temporal and spatial dimensions. This scholarship proposes to examine work practices ethnographically as a helpful way to build narratives about technology in a bottom-up fashion. Finally, I outline a set of concepts and metaphors that serves as groundwork to conduct an ecological analysis of the internet of things.

Social constructivism in studies of technology

The study of technological change has been a central concern in the research programme of science and technology studies (STS) inspired by the sociology of science and the empirical explorations of science in the making (Woolgar, 1991). Early enquiries in the 1980s ascribed to an interpretivist/social-constructivist tradition that ran counter to the post-Enlightenment separation between science, objectivity and nature on the one hand and subjectivity, culture and the social on the other (Sismondo, 2009).

Conversely, social constructivism conceives knowledge and artefacts as the product of the *work* of scientists and engineers. The metaphor of construction has a range of implications in regards to what it means to perform such work. Science and technology, in this view, are contingent on and deeply embedded in ongoing social, economic and political relations. In other words, before facts and artefacts are widely adopted and stabilised, scientists and engineers go through painstaking efforts of validation, negotiation and persuasion (Latour, 1987). 'The construction of facts and machines', as Bruno Latour argues, 'is a *collective* process' (1987, p. 29 emphasis in original).

Going a step forward, not only artefacts and knowledge are social constructs, but the natural and social orders 'co-construct' or 'co-produce' one another. As Sheila Jasanoff (2004) argues, '[k]nowledge and its material embodiments are at once products of social work and constitutive of forms of social life; society cannot function without knowledge any more than knowledge can exist without appropriate social supports' (p. 2). In the vocabulary of STS, the descriptor 'sociotechnical' is used to capture the interplay between technology and the social world. In this study, 'technology' and 'artefacts' are understood in the sociotechnical sense; that is, as constructed by humans and ridden by the social, economic and political conditions of their creation.

In the next subsections, I shall discuss three broad theoretical programmes which are frequently alluded to in the repertoire of technology studies and whose contributions are relevant for articulating a theoretical foundation for this thesis.

The social construction of technology

The SCOT programme proposed a conceptual framework for the empirical study of technology inspired by the 'strong programme' of science studies (Pinch and Bijker, 1984). With roots in the University of Edinburgh, the strong programme established a principle of symmetry for the study of scientific controversies which involved impartiality in the assessment of scientific claims: 'It would be impartial with respect to truth and falsity, rationality or irrationality, success or failure. Both sides of these dichotomies will require explanation' (Bloor, 1976, 1991, p. 7). These tenets were then adapted in the study of technological change to, for example, establish an impartial and symmetrical consideration of successful and failed technologies. An import from the strong programme, for instance, is the concept of *interpretive flexibility* which refers to the capacity of relevant social groups (such as consumers or designers) for assigning different meanings to artefacts (Bijker, Hughes and Pinch, 1987; Bijker and Law, 1992).

The idea that artefacts can be interpreted in multifold ways opens a wealth of possibilities in regards to how artefacts are used and constructed. Still, while the opportunities for interpretation could be potentially endless, people eventually reach compromises analogously to how scientific consensus takes place. Over time, SCOT's proponents argued, artefacts stabilise and reach closure, which manifests in the subsiding of problems or the perception of such by 'relevant social groups' (Bijker, Hughes and Pinch, 1987; Misa, 1992).

Actor-network theory

Conjointly, a widely influential theory of technology and society is actor-network theory (ANT) advanced by Bruno Latour, Michel Callon and John Law. The concept of actor-networks seeks to explicate the making of science and technology (or technoscience), by looking at the *associations* between human and non-human actors (or actants) (Collins and Yearly, 1987; Latour, 2005). One of the main contributions of ANT is the notion that humans could delegate agency to artefacts (non-humans), thereby bestowing them with the ability to *act* in much the same way as humans. This flattening of ontological categories delineates a heterogeneous or hybrid field of interaction between humans and non-humans (Callon and Law, 1997).

For ANT, successful or stable technoscience is seen as the manifestation of an alignment of interests or the establishment of alliances among hybrid actors towards a common goal (Latour, 1990, 2005). According to Callon (2004, p. 3): 'Goods and services have a social life; they go from hand to hand and change along the way. Each actor involved reconfigures and reshapes them depending on her needs and conceptions. Adopting an innovation means adapting it. This is why it is important for the design work to include all those who are going to be concerned by the innovation, and why it must be as open as possible'. The methodological approach of ANT entails, on the one hand, the close (ethnographic) examination of science and technology in the making, with the goal of opening the locales of technoscientific production to the eyes of 'outsiders' (Latour, 1987). On the other hand, it relies on semiotics as a tool to analyse text, discourse and other linguistic and non-linguistic sources of meaning and signification (Callon and Law, 1997). In this sense, the representations and interpretations of the worlds of scientists and engineers that emerge from ANT enquiries are not neutral and demand a process of translation (Latour, 1987).

Actor-network theory has been widely used in a diversity of empirical domains, but it has also been the target of strong criticism due to its methodological shortcomings. While ANT stands as a new sociology of technology that attempts to break with previous systemic understandings of the world (Latour, 1990; Callon, 2004), it remains agnostic to questions of power. A strength of ANT has been its radical commitment to symmetry, which is operationalised in the rejection of essentialist dichotomies such as society and nature, humans and non-humans, truth and falsity (Law, 1999). Yet, this very strength has also been the target of criticism. ANT has, for instance, been accused of moral relativism (Latour, 1990) and criticised for having a too-narrow view of its object of study, thereby being blind to broader political, cultural and economic factors (Williams and Edge, 1996).

A similar problem stems from ANT's focus on the agency of key actors which leads to a tendency to emphasise the work and intentions of influential nodes of the network (both positive and negative). In this way, the analysis risks underplaying the role of marginal and excluded groups, but also seems to remain blind to potential and implicated users as well as to non-users (Sismondo, 2009). Some feminist scholars, for instance, have distanced themselves from ANT due to its failure to address questions of gender, power and the invisible work behind technoscientific achievements (Star, 1990; Wajcman, 1991). This problem is also apparent in SCOT due to its exclusive preoccupation with *relevant* social groups.

The social shaping of technology

The third perspective is the Social Shaping of Technology (SST) initially formulated in an edited collection by Donald MacKenzie and Judy Wajcman (1985) and further delineated by Robin Williams and David Edge (1996). Unlike the previous two approaches, the social shaping of technology is not a standalone theory but an assemblage of concepts and insights that builds on social constructivism. The 'broad church' of SST, Williams and Edge (1996) claimed, was proposed as a unifying intellectual programme that overcomes the drawbacks of its predecessors and contributes to technological innovation policy and practice. The questions posed by SST scholars challenged the longstanding historical and sociological assessments of the effects of technology on society based on linear innovation models, instrumentalist accounts of technology and beliefs in *technological determinism*.

Technological determinism is a simplistic, yet influential theory of the relationship between technology and society holding that, thanks to its inner attributes, technology constitutes a force that dictates history and has direct transformational effects on society (D. MacKenzie and Wajcman, 1985; Sismondo, 2009). In particular, the opposition to technological determinism lies at the core of theories of co-construction or co-production and has galvanised a pragmatic research agenda on the social shaping of technology.

A lasting issue with accounts of science of technology has been that of drawing boundaries between them (D. MacKenzie and Wajcman, 1985). A frequently cited argument has been that technology is the result and ultimate goal of science; or that technology is applied science. This argument lies at the core of linear and one-sided conceptions of innovation which have been widely used in policy for scientific research in the centres of knowledge production. Yet, this view is problematic in that it implies that science is the sole source of technical knowledge. This not only underplays the existence of other sources of technical knowledge but also the influence of technology (e.g. scientific equipment) over science (Sismondo, 2009).

Techno-determinist accounts are also biased towards successful technology which understates the possibilities for failed technologies, thereby giving way to idealised narratives of innovation that often revolve around rather glorified descriptions of individual inventors (Williams, Stewart and Slack, 2005). As a consequence, accounts on the history of technology suggest an orderly and inevitable trajectory of development (Bijker and Law, 1992). Such thinking has been strongly criticised in STS scholarship, not only due to a concern with Whig views of history but because it pervades future-oriented discourse reinforcing hyped narratives of technological progress.

However forcefully rejected in numerous analyses, technological determinism remains a topic of intense debate (Wyatt, 2008). Early SST scholars insisted in that their concerns with technological determinism do not presuppose that technology does not have effects on society[7], but that its effects cannot easily be singled out from economic,

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[7] While SST is preoccupied with the normative drawbacks of technological determinism, it recognises that technology has effects on society. Steve Woolgar criticised early SST scholars for not elaborating on this ambivalence, which he saw as a contradiction with the ultimate goal of SST of dismantling technological determinism (see Woolgar, 1991).

political and cultural factors (D. MacKenzie and Wajcman, 1985; Woolgar, 1991). Rather than focusing on the effects of technology on society, the approach of social shaping of technology is to interrogate 'what shapes technology in the first place, before it has its effects?' (D. MacKenzie and Wajcman, 1985, p. 8). In this sense, SST invites us to open the 'black box' of technology and unveil its content by examining not only the materiality of technology but the processes and practices involved in innovation (Russell and Williams, 2002).

A second wave of SST research incorporated insights from SCOT and ANT as well as from feminist scholars and other disciplines such as economics, history of science and technology, sociology and political sciences (Russell and Williams, 2002). The extended focus of SST centred on issues of technology appropriation, diffusion, marketisation, the alignment between designers and users and the intervention with innovation policy (Mackay and Gillespie, 1992; Sørensen, 2002; Sørensen and Williams, 2002).

In theorising innovation, the concepts of *sociotechnical alignment*, *entrenchment*, *path dependence* and *lock-in* have been used by SST authors to explicate technology stabilisation, or what has been previously registered in SCOT as *closure*. In turn, interpretive flexibility has been confronted with studies that found patterns in the way certain technologies are appropriated, pointing to the need to build a typology of technologies, with its own deterministic risks (Lie and Sørensen, 1996; Sørensen and Williams, 2002). For instance, empirical research on information and communication technologies (ICTs) emphasised on their distinct malleability and potential for further configurations by users (Kubicek, Dutton and Williams, 1997; Williams, 1997; see also next section). Indeed, one of the core aims of SST has been to problematise the role of users in innovation and in so doing producing insights for designers, engineers and policymakers (Russell and Williams, 2002).

Some analytical delimitations

Framing innovation as a collective process

A core insight from the social constructivist theories of technology and one that underlies the analytical work in this study is that technological progress does not follow a determined path into the future. Instead, the spheres of technology production are plagued with choices and influenced by a range of cultural, economic and political factors. In other words, technological trajectories are highly unpredictable, and multiple outcomes are possible (Williams and Edge, 1996). This insight underpins the idea that technology is socially shaped and begs the question of what influences the choices made at different moments in the development and implementation of technology.

An approach to this question, as proposed by Knut Sørensen, is to investigate the symbolic content (as opposed to just the materiality) of technological artefacts and the ways in which meaning is shaped by culture and contextualised temporally and spatially[8] (Sørensen, 1996). The unpredictable nature of innovation suggests that artefacts are not readily assimilated and put to work without regard to social practices and their locales of use. Instead, there is a process of appropriation, meaning-making, familiarisation and contextualisation associated with the adoption of artefacts (Lie and Sørensen, 1996; Sørensen, 2002). An analytical approach to investigate such incidents is to look into how knowledge is accrued and exchanged as sociotechnical entities evolve (Sørensen, 2002).

This approach offers a vocabulary for dealing with change and a heuristic to study the way actors make their decisions and reach agreements on the basis of learning. Sørensen's (1996) approach entails an identification of the different sorts of iterative social learning processes in innovation. Perhaps the most apparent forms of learning comprise *learning by using* or *learning by trying* which constitute ways for people to gain skills and experience in their interaction with artefacts and in so doing optimise processes (Sørensen, 1996). But the success of technologies may also involve a more direct nexus between the worlds of designers and users, achieved in a process of *learning by interacting,* which is sometimes mediated by external actors. This points, for instance, to direct engagement activities between *designers and users* but also to the existence of intermediaries who play a crucial role in helping to bridge and translate knowledge between separate domains (Stewart and Hyysalo, 2008). It

[8] This strategy is inspired by the work of semioticians who foreground meaning and signification through the metaphors of translation (Collins and Yearly, 1987), technology as text (Woolgar, 1990) or technology as script (Akrich and Latour, 1992).

should be noted that this formulation implies a separation of the roles of designers and users, an issue I shall address below.

Standard developers and policymakers are also implicated in instances of learning. Indeed, conventions of practice, alliances and regulations might be directly intended towards fostering some technologies over others depending on the particular conditions. The ongoing process of high-level negotiation and technical adjustment has been characterised by Sørensen (1996) as *learning by regulating*. This form of learning is of relevance to accounting for the attempts of regulators, firms and standard developers to steer or encourage innovation. Indeed, the notion that innovation continues to take place during the diffusion of artefacts has been widely recognised by managers, designers and policymakers and has led to the articulation of open innovation strategies and policies (Fleck, 1988; von Hippel, 2002; Bogers and West, 2012).

The heuristic of social learning has been helpful in studies of information and communication technology (ICT) where the interaction between collaborating actors have been brought to bear on dispersed forms of innovation (Procter and Williams, 1996; Procter, Williams and Cashin, 1996; Williams, Stewart and Slack, 2005). It has been observed, for instance, that the intentionally 'unfinished' status of certain information technologies (e.g. computers, software or the internet) affords a set of options for users to appropriate, configure and interpret them according to their needs (Fleck, 1994; Williams, Stewart and Slack, 2005; see also next section)[9].

While system developers could rely on gathering information about users through experiments, trials, market research, there could also be strong incentives for them to *innovate with users* or leave users to innovate by themselves. Developers, for instance, might be inclined to deliver generic artefacts, relying instead on modular and flexible architectures as a means to target larger audiences (Pollock, Williams and D'Adderio, 2016). Such a mode of work is perhaps best illustrated by the 'open-sourcing' of processes, where development is explicitly reliant on principles and protocols of

[9] This insight falls in line with similar conceptualisations in other strands of research. Notably, scholars of information infrastructures have drawn strongly on the concept of generativity to highlight how the flexibility of information systems facilitates the creation of new functions, uses and applications (see Henfridsson and Bygstad, 2013).

collaboration. Here lies an understanding of innovation as iterative, incremental, experimental and ultimately, a collective process.

Framing innovation as a collective process implies a recognition that the decisions of system designers, developers and architects are continuously influenced by a host of external factors and various other actors involved in the implementation and use of systems. This framing calls for attention to multiple locales of action as well as different stages of evolution. A productive approach within STS has been to observe multiple locales, temporalities and types of work practice and in that way weave detailed narratives of the whole spectrum of innovation stages (Williams, Stewart and Slack, 2005).

But the idea of innovation as a collective process also underlies the premise that various actors are in a position to work together in the production of technology. This begs a political question of *who is part of the collective process*, and *who is not?* and concurrently, what locales of actions are to be included in the research design? The innovation collective, for instance, could be understood as comprised by an R&D team, but also by its extended network of support, production and marketing teams, or even by external actors such as collaborating firms, suppliers and customers. It thus seems crucial to uncover who are the members of innovation collectives. In contrast with the conception of ‘open innovation’ approaches of inter-firm collaboration, this study problematises the allusion to the involvement of non-corporate actors in innovation such as users. More specifically, the purpose is to unpack what is meant by the broad idea of user innovation (see e.g. von Hippel and von Krogh, 2003; Baldwin, Hienerth and von Hippel, 2006; Bogers and West, 2012).

Who are the users?

As discussed in the last chapter, the literature has given a great deal of attention to users and there is a growing interest in investigating the active involvement of users in innovation. Yet to speak of innovation by users, it is first necessary to do a careful unpacking of the conceptions of ‘the user’. While the term is prevalent among practitioners as well as in the innovation literature, it carries multifold connotations which are often unhelpfully bundled up in discussions of users’ relationships with technological change. While users are known to take up active roles in innovation processes, their contributions may be highly uneven depending on their knowledge and specific conditions.

In the field of design theory, Johan Redström (2008) argued for a shift of paradigm from merely looking at users as pre-existing entities who are able to adopt artefacts in an orderly and predictable fashion to an assessment of how objects are used in a specific context. For Redström, the user shall be seen not only as a useful prop to inform design prior use but also as an emerging status that is enacted by an actor *during* the use of an artefact. In other words, not only designers prefigure and incorporate ideals of use and users during the early stages of design and development, but actual users reinterpret and design objects during their use, often in unexpected ways (Akrich, 1995; Redström, 2008). For the purposes of user-centred design, the notion of the user could thus be formulated in a semiotic sense, that is, 'as imagined by the designers of a technology' (Akrich, 1995; Oudshoorn, Rommes and Stienstra, 2004), or relationally, in terms of the relevant practices linked to the use of technology (Hyysalo and Johnson, 2015).

While these conceptions of users are helpful for the work of designers, they give us a narrow conception of the scope of action for users with respect to designed artefacts. At this stage, I shall now once more turn to the work of feminist scholars on problematising the relationship between users and technology (Oudshoorn and Pinch, 2003) which is of significance here to articulate an empirical approach to studying the involvement of non-conventional actors in innovation.

As discussed in Chapter 2, the gendered division of labour in technology production and the gendered nature of artefacts have been widely explored empirically by studies of technology in the making and technology in use (Cockburn, 1993; Lie and Sørensen, 1996; Oudshoorn, 2003; van Oost, 2003; Oudshoorn, Rommes and Stienstra, 2004). The analytical commitment of this scholarship has been to include invisible actors and work practices in order to problematise power relations in the production of technology and also to inform the design of systems (Star, 1990; Suchman, 2002a). Methodologically, investigating users is a call to study technology *in context* and not only the *typical* sites of technology production. For the study of technology, this entailed an extension of the empirical focus to the various 'downstream' sites where technology is implemented and used (Williams, Stewart and Slack, 2005).

Feminist scholars have shed light on how users engage actively with design practices and, in so doing, they have challenged the predominant designer/user binary within design and innovation discourses (Oudshoorn and Pinch, 2003, 2007; Wajcman, 2010). While it has been recognised that numerous non-conventional actors engage in practices of configuration and adaptation, the scope of action of certain *advanced* and *expert users* may be even broader. For instance, some users may partake, not only in design, but also in maintenance, repair, operation, and infrastructure-building activities. This insight offers a useful methodological underpinning to speak about the roles of users insofar as it challenges the common assumption that users and designers necessarily operate in separate spheres of action.

However useful as a rhetorical device, the term 'user' is problematic in itself as it may gloss over the uneven forms of involvement in innovation. Hence, my approach, for now, is to avoid the loose invocation of the term, avoid polarising terminology that implies a division between users and developers, and depart from expressions such as 'user-led', 'user-driven' or 'user-centred'. In so doing, the aim is to uncover the myriad relations and ways in which heterogeneous actors contribute to innovation. A concrete way to do this is by specifying the role or positionality of users and looking for more accurate labels. One can equally find alternatives in the vocabulary of contemporary information systems developers; for example, tenants, initiators, implementers, integrators or developers.

Grappling with complex information systems

This thesis is concerned with scrutinising sites collaborative action located under the broad rubric of the internet of things. Not only I am interested in the production of discrete artefacts and applications but in the construction of the information systems that underlie their operation. So far, I have emphasised the need to observe the sites of technology design, development and use in order to avoid linear conceptions of innovation. Yet, in the context of complex information systems, this task is complicated by the infrastructure-like features of systems that extend across geographical domains, multiple organisations and long temporalities (Williams, 2019).

In this section, I delve into the considerations that need to be addressed in the study of the internet of things. To that end, I would like to draw attention to a cognate body of STS-informed research which has been concerned with the study of large-scale information systems and the difficulties surrounding their construction, dynamics of change and long-term stability (Edwards *et al.*, 2007; Jackson *et al.*, 2007). This scholarship characterises complex systems in terms of infrastructure and provides a set of critical conceptual and methodological considerations for this study.

The language of infrastructure

The Oxford English Dictionary defines infrastructure as 'a collective term for the subordinate parts of an undertaking'. The term is broadly used to describe the foundational elements of modern systems and services such as power and water supply, transport and telecommunications. Although these systems may initially stand out as new and remarkable, over time, they become an invisible and indispensable constituent of the fabric of society. To study infrastructures is thus to look into the most pervasive yet largely taken-for-granted facets of technology (Edwards, 2002). Various accounts of the construction of large-scale technical systems have been written from sociological and historical perspectives (Hughes, 1983; Fischer, 1992; see e.g. Abbate, 1999). A widely-cited work is Thomas Hughes' (1983) account of the construction of electric power infrastructure in Western society. Hughes traces de diffusion of the technology as it matures, gaining 'momentum' through reaching a critical mass of users. Writing from a social constructivist perspective, Hughes identifies linkages between long-term development patterns and the role of standards, legal instruments, politics and organisation in the evolution of infrastructures (Hughes, 1987).

Going a step further from socio-historical accounts, scholars have viewed infrastructures not only as an object of study but as an analytical and methodological tool (Edwards, 2002). This calls for an ontological shift in the conception of infrastructures from just things to, e.g. a series of relationships (Star and Ruhleder, 1996), sociotechnical institutions (Edwards, 2002), or a sensibility (Jackson *et al.*, 2007). For instance, in line with the feminist sensibility of foregrounding invisible work practices, Susan Leigh Star has proposed to recognise infrastructures not merely as material objects but in 'relation to organised practices' (Star, 1990; Star and Ruhleder, 1996). This relational perspective proposes to formulate ethnographic descriptions of information systems in order to problematise the different positionalities and overlapping roles of the different actors involved in their construction (Star, 1999; Star and Bowker, 2010). The ethnographic vantage point offers a productive mechanism to question the uneven relationships and conceptions of infrastructure that emerge from a diversity of actors. To cite Star: 'For a railroad engineer, the rails are not infrastructure but topic. For the person in a wheelchair, the stairs and doorjamb in front of a building are not seamless subtenders of use, but barriers' (Star, 1999, p. 380). In this sense, studying infrastructures ethnographically means to locate and unearth the everyday processes of design, construction, maintenance and operation (Bowker, 1994; Suchman, 1995; Star, 1999).

Studies of infrastructure have been primarily motivated by a need to inform their design and successful implementation (Hanseth, Monteiro and Hatling, 1996; Bowker *et al.*, 2010). The initial scope of this strand of research has been around large-scale work-oriented systems. Much work was conducted on *cyberinfrastructures* in the U.S. since the positioning in the public discourse of the 'information superhighway' which signalled a political will to build shared information facilities and services to support scientific research (Edwards *et al.*, 2009). The agenda for the study of cyberinfrastructures, and similar attempts elsewhere (e.g. eScience and e-infrastructure), aimed to include not only technical but social and political aspects (Edwards *et al.*, 2009; Pollock and Williams, 2010). According to Geoffrey Bowker and colleagues 'understanding the nature of infrastructural work involves unfolding the political, ethical, and social choices that have been made throughout its development' (2010, p. 99).

Growing out of the research on cyberinfrastructure, the term 'information infrastructure' has gained purchase in STS and information systems research as a broad concept[10] that gathers common features such as widespread knowledge and data sharing, the embodiment of standards, the tensions between the global and the local, and the need for long term sustainability (Hanseth, Monteiro and Hatling, 1996; Monteiro and Hanseth, 1996). Hanseth and Lyytinen define information infrastructure as 'a shared, evolving, heterogeneous installed base of IT capabilities

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[10] While this use is a narrowing down to non-public situations, the concept is broadly employed in the study of various (often overlapping) types of infrastructures such as the internet, business infrastructure, corporate infrastructure and different sorts of related functionalities such as services, collaboration or communications (Hanseth and Lyytinen, 2003).

among a set of user communities based on open and/or standardized interfaces' (2003, p. 9). While this conception of information infrastructures is helpful, it is necessary to further demarcate the ambit of infrastructure, 'IT capabilities' and 'user communities' in line with the context of the internet of things. The heightened focus on the collection and handling of data for purposes of automation, and the heterogeneity of 'users' offer pointers to such an aim. As discussed in Chapter 6, 'data infrastructures' arises as a more accurate analytical term in the context of the internet of things.

In the study of infrastructures, the question of change seems to be directly implicated with that of long-term stability. While infrastructures rely heavily on processes of standardisation for ensuring interoperability and cohesion between disparate components, they are also intended to support the production of innovations and remain flexible for future changes (Hanseth, Monteiro and Hatling, 1996; Star and Ruhleder, 1996). In most cases, infrastructures are intended to be durable and far-reaching, and therefore they demand attention to the temporal and spatial dimensions. To cite Paul Edwards, 'the notion of infrastructure invokes possibilities of extension in time, space, and technological linking that go beyond individual systems' (2002, p. 13). Empirical studies of information systems for scientific research, for example, have shown that, compared to traditional IT projects which are bound to relatively short periods of 3 to 5 years, information infrastructures are meant to last for multiple decades (Karasti, Baker and Millerand, 2010).

Thinking seriously about temporality has encouraged methodological innovations such as posing the question of *when* as opposed to *what* is infrastructure? (Star and Ruhleder, 1996), and verbalising the term as 'infrastructuring' (or 'to infrastructure') to emphasise the importance of ongoing work (Karasti and Baker, 2004; Star and Bowker, 2010). In Chapter 6, I invoke the notion of infrastructuring to convey a sense of continuity in the descriptions of work.

But attention to temporality also seems to demand a long-term commitment with the empirical study of infrastructures (Karasti and Baker, 2004; Ribes and Finholt, 2009). To fulfil this exigency, various scholars have suggested longitudinal studies as the ideal type of research design (Pollock and Williams, 2010; Karasti and Blomberg, 2018). Although such a commitment requires a privileged availability of time and resources, multisite and long-term (biographic) studies have been deployed as a means to assess the full 'life cycle' of technologies (Pollock and Williams, 2010). Dealing with the long term is a salient methodological challenge in the context of a time-constrained doctoral project which needed to be considered reflexively in the formulation of the research design (see Chapter 4).

Closely linked with the longevity of infrastructures are the issues of geographical scale and growth which have implications at the micro, meso and macro levels of analysis (Edwards, 2002). This thesis is primarily concerned with the micro-level where scaling up appears mostly as a matter of user populations and the influence of individuals and communities in shaping infrastructures locally. This approach is oriented at the assessment of the everyday construction and operation of infrastructure as a means to arrive at detailed descriptions of infrastructure. As I describe at length in Chapter 4, the ethnographic exploration of a geographically distributed infrastructure entails a familiarisation with a range of actors and their everyday efforts of institutional and technical liaison for interoperability, knowledge transfer and coordination. Yet, the micro-level analysis should be read in context with the meso and macro scales in order adequately to grapple with long-term patterns of development and locate events historically (Edwards *et al.*, 2007; Jackson *et al.*, 2007). At a meso level, for instance, it seems relevant to ask the question of how infrastructures are governed and regulated and focus on the institutional, political and economic efforts to organise infrastructure. In turn, a macro-level perspective seeks to reveal long-term trends of infrastructural development in the context of globalisation and post-industrial capitalism. Studies of infrastructure have drawn on organisational theory, economic history and science and technology studies in order to explain issues of growth, institutional alignment, long-term organisational and technical sustainability, stabilisation and change. Concepts from network economics such as network externalities, lock-in, path dependency and self-reinforcing effects have, at least to some extent, been useful to explain the dynamics of growth and stabilisation (Hanseth, Monteiro and Hatling, 1996).

Lastly, given the complex issues of scale, time and heterogeneity, a recurring theme in information infrastructures research is that of agency and the possibility for control. From the perspective of designers and managers, dealing with problems arising as different networks and standards are rolled out, interlinked and embedded with other systems may seem an insurmountable task. In studies of corporate infrastructures, this issue has been problematised as a paradox of control. That is, as infrastructures extend across wider domains (including other infrastructures), unintended side-effects become more salient, hence limiting the possibilities for control and the repertoire of designers' choices (Ciborra, 2000; Hanseth and Braa, 2000).

Rather than being the direct result of the work of managers or designers, infrastructures seem to unfold organically and incrementally through coordination and collaboration (Edwards *et al.*, 2007). Over time, certain features of infrastructures become entrenched and irreversible, making them more resistant to change (Hanseth and Monteiro, 1998). In order to deal with uncertainty and unintended effects, managers and designers may be inclined to give up opportunities for control in favour of simplicity and enhanced flexibility aimed at granting more autonomy to users (Ciborra and Hanseth, 1998; Ciborra, 2000; Hanseth and Braa, 2000). Standardisation, generification, interfacing and modularisation are some of the strategies identified in empirical studies to make infrastructures flexible and future-proof (Hanseth, Monteiro and Hatling, 1996; Aanestad and Jensen, 2011; Pollock, Williams and D'Adderio, 2016).

The language of infrastructures offers a promising framework to grapple with the multidimensional complexity of systems such as the internet of things. A first analytical pointer for this study is thus to shift from a focus on discrete artefacts to an infrastructural description of the internet of things. Methodologically, the proposal is to build an account of infrastructure through the work practices that surround its construction. I will, therefore, focus on the practices of network design, development, deployment, maintenance, operation, monitoring, testing. Formulating the analysis in these terms calls for a sensibility of the heterogeneity of actors and practices, mapping the multiple sites of action and the incorporation of time as a critical dimension of analysis.

Making a relational linkage to materiality

In scrutinising the role of different actors in the construction of complex systems, the question of materiality is not a trivial one. The possibilities for actors to act collectively are contingent on their circumstances as much as the options afforded to them by tools for collaboration and flexible systems. Researchers of information infrastructures frequently invoke the concept of generativity –or the potential for technology to enable further autonomous configurations which are contingent to the context—as a heuristic for explaining how certain features of technology are implicated in innovation processes. For instance, personal computers and the internet have been portrayed as the archetypical examples of generative technologies insofar as they are flexible enough to enable novel and unexpected configurations, uses and discursive representations, while at the same time capable of constraining unlawful behaviour (Zittrain, 2006). Similar examples are used in studies of technology to illustrate the characterisation of ICTs as highly amenable to configuration and appropriation by users (Fleck, 1994; Williams, 1997).

The generativity argument has a footing either in an interpretivist tradition or more recently in a critical realist one (see Henfridsson and Bygstad, 2013). The former group of scholars theorise infrastructure development drawing on actor-network theory whereby humans are viewed to delegate agency through inscribing their intentions into artefacts (non-humans) (Hanseth and Monteiro, 1997; Ciborra, 2000). In line with this view is the relational assertion that while technologies like the internet can be made to be generative, such properties manifest only at the point of use (Nielsen and Hanseth, 2010). In contrast, some authors within the Information Systems camp ascribe to critical realism whereby technology is assumed to have attributes independently of human's experience or interpretations of it (a realist ontology), while knowledge is considered to be the product of the work of humans (a relativist epistemology) (Mingers, 2004). These scholars engage more directly with materiality with the goal to identify causal mechanisms for explaining successful innovation (Bygstad, 2010; Henfridsson and Bygstad, 2013). The core assumption is that certain attributes of infrastructures are essential to facilitate or encourage new uses, configurations or interlinking with other systems. At the same time, due to their rigidity and dependability on existing technical layers, infrastructures may also constrain certain practices and even hinder innovation (Henfridsson and Bygstad, 2013).

The way materiality is dealt with in studies of technology can be located within a longstanding debate in STS between constructivism and realism (Grint and Woolgar, 1997; Heur, Leydesdorff and Wyatt, 2012). The social-constructivist tradition (and particularly SCOT) has been accused of underplaying the role of materiality and having a radical commitment to interpretive flexibility (Verbeek, 2005). In turn, actor-network theory deals with materiality by levelling the ontological status of humans and non-humans, this being its prime method for explaining the mutual effects of technology and society. Along the same lines, authors ascribed to the social shaping of technology have remained sceptical to the possibility of unbounded interpretive flexibility. As Sørensen argues, 'material objects cannot be taken as completely malleable. Users are *constrained and supported* by material as well as cultural features of the situation' (1996, p. 13 emphasis added). These engagements with materiality acknowledge the importance of the constraining and enabling features of technology while still avoiding buying into *a priori* causal effects.

To avoid falling into technological determinism, authors often invoke the language of affordances to allude to the supporting and constraining capacity of technology (Hutchby, 2001; Hsu and Pinch, 2008). The concept of affordances, as developed originally within the psychology of perception by James Gibson (1979), refers to the possibilities offered by an entity (e.g. a tree, an artefact, an animal) for perception or action by an observer, regardless of whether these are acted upon. The concept was further developed by Norman (2013) for design theory, where he describes it relationally as 'jointly determined by the qualities of the object and the abilities of the agent that is interacting' (p. 11).

According to these definitions, the affordances of an artefact may stem (albeit not necessarily) from its intrinsic material or the attributes inscribed into them by design. Yet, they do not determine the actions of an actor. While designers might have clear goals in mind when conceiving technical features, the interaction with such features is contingent on their readiness as much as on the specific context, social norms, or the cognitive abilities of the implicated actors. While a wooden chair affords the action of sitting, it may also be used for standing, as a doorstop or as firewood. Constraints are also crucial in this consideration insofar as the affordances of objects may impose limits to what actors can accomplish. There is only so much an artefact will allow one to do: they have a limited range of possible interpretations (or limited interpretive flexibility). However, constraints may also be due to contextual circumstances such as accessibility, conventions of practice or governing rules. A programming language, for instance, will afford a bigger range of options to users with more previous knowledge and better access to computing resources.

Ian Hutchby has recast the concept of affordances as 'functional and relational aspects which frame, while not determining, the possibilities for agentic action in relation to an object' (2001, p. 444). A relational description of affordances aims to find a middle ground between boundless interpretive flexibility and the realist possibility of artefacts supporting or constraining actions. In other words, affordances are defined as relations insofar as the possibilities for enabling and constraining action are contingent on the context and the implicated actors[11]. In line with the assumption that technology is socially shaped, the role of technical features and materiality shall be better understood with attention to the context and circumstances. As stated by Williams et al. (2005, p. 15) 'outcomes arise through the interaction between artefact and its social setting of use. Rather than imposing particular uses and outcomes, artefacts offer a range of constraints and affordances in their use. And the fluidity and flexibility in use, which may be "designed into" many artefacts (especially ICTs) suggests that some artefacts may be associated with an extremely wide range of outcomes'. Whilst technology and society mutually shape each other, the range of choices and possible outcomes is not boundless but depends on what artefacts and systems afford actors to do as well as the particular context and circumstances.

In the empirical chapters of this thesis, a good deal of attention is given to the 'material' properties and technical aspects of IoT artefacts and systems. In the exploration of the field as well as in the analysis, I delve into the design of a modular network architecture; the development of open source software and graphic interfaces; the coupling of different technical elements through the use of standardised interfacing and protocols; and the manufacturing, commissioning and operation of hardware. In the analysis, the specificity of technical features is always recognised with attention to work practices. Not only specific functions and features are used as mechanisms to *encourage* particular uses over others, but they carry symbolic meaning that is used in the construction of narratives about decentralisation, openness, neutrality and collaboration.

In the realm of the internet of things, it is crucial, for example, to take into account the affordances of wireless communication standards (e.g. capacity, speed and latency)

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[11] Interestingly, Trevor Pinch has more recently reacted to critics accusing SCOT of overlooking materiality with an acknowledgement of the role of supports and constraints (see Pinch, 2010, p. 85).

and recognise their implications for design, implementation and use of networks and connected devices. Some of the communication protocols employed for connected devices, for instance, operate on portions of the radio spectrum reserved for industrial, scientific and medical (ISM) purposes. Regional conventions for the use of these frequencies define distinct technical constraints of use of the radio spectrum, transmission power and balance of load which bear on the possibilities of manoeuvring, configuring and deploying networks and connected objects. Similarly, while flexible technologies offer a wealth of possibilities for innovation, their use is also constrained by institutional, cultural and regulatory conditions.

An ecological analysis of the internet of things

The proposal for this study is to combine theoretical insights and methods from SST and studies of infrastructure to grapple with questions of change in the internet of things. Both approaches can productively extend and complement each other (Williams, 2019; Monteiro *et al.*, 2012; Monteiro and Hanseth, 1996). On the one hand, building on the sociotechnical approach and the framing of innovation as social learning, I pay particular attention to the flows of knowledge between actors in my analysis of technological change. This sensibility crucially brings to the fore multiple sites of action beyond the conventional centres of technology production and problematise the role of users and a range of other implicated actors. At the core of the analysis is the notion that technological change is effectuated by processes of mutual learning between a range of heterogeneous actors rather than constituted as a straightforward process of invention, refinement and commercialisation.

On the other hand, the study of the construction of data-oriented networks calls for an adequate method to deal with the complexity of systems that straddle multiple domains, spaces and extended timeframes. In this sense, a helpful import from studies of infrastructure is the shift of the unit of analysis from discrete artefacts to infrastructures (Karasti, Baker and Millerand, 2010; Monteiro *et al.*, 2012). This is not just a rhetorical exercise, but it entails a reassessment of the articulation of innovation in terms of products to imaginaries of complex and long-lasting sociotechnical formations involving individuals, communities and institutions. Some of the key analytical dimensions of infrastructures, for instance, include their embeddedness in existing systems, the embodiment of standards, their long-term horizons and their extensive reach and scope (Star and Ruhleder, 1996; Edwards *et al.*, 2007).

Based on these broad theoretical tenets, I propose to produce a detailed description of the work surrounding the construction of IoT data networks and applications. As mentioned above, examining work practices is a helpful way to arrive at a more nuanced identification of the role of users and the diversity of contributions to the evolution of infrastructures. But the focus on work practices also comprises a method for reflexive boundary-making of the research field. Recognising the heterogeneity of work offers a useful way to uncover how communities are formed, which actors are expected to be involved and which ones are left out (Star, 1990; Larkin, 2013). This analytical approach has been profitably deployed in participatory design and CSCW research where infrastructure work (or infrastructuring) has been delimitated in terms of their associated empirical sites such as the workplace, the household, the public or specific communities of practice (Star and Strauss, 1999; Pipek and Wulf, 2009; Karasti, 2014). I will apply this strategy throughout my empirical analysis by focusing on actors' expertise and positionality in order to map the field.

Through producing detailed descriptions, I aim to lay out an ecological analysis of the internet of things. This approach intends to bring to the fore the socio-material relations between the entities inhabiting the space rather than focusing on the role of specific actors (Star and Ruhleder, 1996). To do this, I will rely on a set of concepts and metaphors throughout the analysis. The first of them is the concept of 'ecosystem' which has become a key part of the understanding of business, innovation collectives and, more recently, the 'platformisation' of IT services (Jacobides, Cennamo and Gawer, 2018). Ecosystems have been particularly salient in the management literature to describe the various sorts of vertical and horizontal assemblages of interdependent actors organising around a given supply chain, market or platform (Altman and Tushman, 2017). While existing definitions from the management literature might be fitting here, I refrain from ascribing to any of them but instead deploy the term in an interpretivist manner. For instance, the term is used by practitioners, and notably by my informants, as a boundary drawing device to demarcate scopes of influence. In this case, the metaphor of ecosystems is a helpful way to capture the interplay between different actors and institutions that cohabitate a common space of interaction in rather synergetic and complementary ways. Throughout the empirical chapters of this thesis, I offer an ethnographic description of an Internet of Things ecosystem based on my informants' conceptions of membership; I shall however point out, whenever necessary, the overlap or embeddedness with other ecosystems (e.g. 'The Things Network ecosystem' or the 'LoRaWAN ecosystem').

An equally useful metaphor used in the analysis is that of 'arenas' which I deploy in Chapter 7 to schematise a sociotechnical map of the terrain. In STS, the notion of development or implementation arenas has been used to refer the physical and cognitive spaces where actors, artefacts and standards converge in relation the development of products and services (Jørgensen and Sørensen, 1999; Williams and Bunduchi, 2004). This approach is perhaps comparable with the concepts of 'communities of practice' widely used in anthropology for evaluating spaces of social learning (see Wenger, McDermott and Snyder, 2002) or 'social worlds' developed within symbolic interactionist sociology (see Clarke and Star, 2007). Such a representation of the spaces where social learning takes place is aimed at demarcating the scope of action of interacting actors within the ecosystem and identifying how their complementary practices influence the innovation process (Williams, Stewart and Slack, 2005). In the analysis, work practices and artefacts are used as the main criteria to draw the boundaries of innovation arenas. In this fashion, the goal is to identify how the division of labour plays out in the ecosystem. The use of standardised interfaces, for instance, is a critical linking mechanism between different arenas. In the case of the IoT, both virtual and physical interfaces such as authentication protocols, application program interfaces (APIs), graphic user interfaces (GUIs) and physical I/O interfaces lie at the interstices between arenas. Equally so, other non-technical, cognitive types of interfacing (e.g. social events and workshops) may be relevant in the analysis of how complementary competences are woven together (Laurel and Mountford, 1990).

Lastly, in order to delve into how actors endeavour to align their work across different knowledge domains, I will use the concept of 'boundary objects' which was originally formulated by Star and Griesemer (1989) for studying the dynamics of scientific work. Boundary objects constitute actual or metaphorical communicative devices between heterogeneous groups seeking to collaborate without the need for consensus (Star and Griesemer, 1989; Star, 2010). A key aspect of boundary objects is their interpretive flexibility, or the notion that 'they have different meanings in different social worlds but their structure is common enough to more than one world to make them recognizable, a means of translation' (Star and Griesemer, 1989, p. 393). Yet, regardless of their flexibility, boundary objects play a critical role in facilitating the work of different communities and organisations. The symbolic value of boundary objects stems from their relational status; that is, they are collectively shaped and become relevant only at the moment of use (Gal, Lyytinen and Yoo, 2008).

Boundary objects have been a useful mechanism for different groups to convey meaning about new artefacts notably in the development of software, information systems and project management (Levina and Vaast, 2005; Swan *et al.*, 2007; Barrett and Oborn, 2010). Some examples of boundary objects used to bridge different spheres of knowledge in information systems are sketches, visualisations and a range of analogies with physical objects such as buttons, scroll bars, boxes, windows (Henderson, 1991; Williams, Stewart and Slack, 2005). Equally in the realm of the internet of things, and as it will be salient from the findings of this study, heterogeneous actors rely strongly on abstract and concrete boundary objects such as depictions of network topologies, architectural diagrams, roadmaps, technical specifications and other pedagogical materials.

Finally, it seems crucial to forewarn that an ecological analysis of the IoT shall consider the locales of action (arenas) not merely as geographically bounded spaces, but also as virtual and technology mediated. In the context of information systems more generally, a great deal of work is concerned with the development of software and the handling of data and may thus be conducted without the need for physical proximity between actors and artefacts. Software development quite markedly flags the boundless nature of certain technical activities. Pollock et al. (2009, p. 258), for instance, have recommended that 'the conception of the situation of repair be extended to account for the fact it is no longer principally the physical situation (or place-based social relations) that bear the brunt of problem solving. It is for this reason we might think of the place in which repair takes place as an "extended situation"'. Still, despite the apparent feasibility of remote configuration and maintenance of IoT networks, only a portion of infrastructure-oriented work is conducted at a distance. Indeed, a great deal of the efforts is concerned with commissioning and maintaining physical elements with entail a range of highly localised activities such as installing, replacing, assembling and wiring components.

Conclusion

In this chapter, I propose a framework for dealing with change in the development of IoT systems. To do this, I build on the social constructivist tradition within social studies of technology. While I do not ascribe to a particular theory, I draw from concepts and methodologies that have proved to be of great value for advancing a nuanced and critical assessment of innovation. At the core of the analysis is the premise that technology and society are deeply entangled and 'co-producing' one another. One of the most important achievements of such framing has been the challenge of the ostensibly linear trajectories of technological change that have been so prevalent in (Western) science and technology policy. A multifaceted call for empirical enquiry then starts to emerge whereby users need to be recognised as key agents in processes of change.

Having established this broad premise, studying the internet of things calls for an engagement with the complex nature of emerging data networks envisaged to be pervasive and expansive in their scope and scale. It is thus necessary to move beyond the view of technology as discrete products to a recognition of the rather *infrastructural* manifestations of technology. For instance, the increasing digitisation the world through networks of sensors might extend beyond the boundaries of single projects and challenge the conventional processes of artefact development, marketing and commodification. Given their complex nature, infrastructure-like technologies also pose challenges of management, financial sustainability, irreversibility and coordination, which call for careful analysis. The lens of infrastructure studies in this sense flags the need for a recognition of existing technical layers, extended temporalities and multiple domains of influence in the evolution of systems.

The proposal for this study is to arrive at an ecological analysis of the internet of things. Such a framework is applied in tandem with a bottom-up ethnographic exploration and a sensibility towards the infrastructural dimensions of the systems in question. In this way, I intend to move away from the descriptions of IoT as simply a cluster of technologies to a multidimensional view that takes stock of the sociotechnical, geographical and temporal aspects. The ecological analysis necessarily comprises a boundary drawing exercise. To that end, I resource to a set of concepts and metaphors that are helpful to describe the broad space of enquiry and to sort out the relationships between heterogeneous actors. I will thus underpin the ecological analysis in a vocabulary of ecosystems, arenas, interfaces and boundary objects.

In the formulation of a theoretical framework, I have given some important pointers to methodology. On the one hand, I have justified the need to include multiple sites of action in the analysis of technological change and to focus on work practices as a means to foreground the distinct contributions of actors. With this approach, the aim is to move from a blanket application of 'users' as a unit of analysis to a more nuanced recognition of non-conventional actors. On the other hand, the considerations of temporality and geographical scope are crucial for the formulation of a feasible research design. As I will outline in the next chapter, the ethnographic enquiry is informed by an immersion at the early stages in the life of a global internet of things initiative. This presents a unique opportunity for observing change at a critical moment, while technical choices abound and before sociotechnical formations stabilise and networks become widespread or global. Yet, at the same time, the analysis needs to be read in context with attention to past developments, existing structures and reflexive awareness of the moment of the research intervention.

Chapter 4 – Research Design: methodology, fieldwork, ethics and reflexivity

In this chapter, I flesh out the research design devised for this study which builds on an in-depth account of a global decentralised internet of things initiative known as 'The Things Network'. I begin by recounting the groundwork conducted prior to the selection of the case and the formulation of the research questions. I then outline the rationale behind preparing a research strategy and a plan of action for data collection. In doing this, I justify my methodological commitments to the use of the case study method and ethnography. The particular circumstances of the case called for a flexible methodology and a combination of techniques of observation and sources of data. The emerging research design thus entailed a multi-site ethnographic exploration which has been tailored to the changing conditions of the field. I give an account of the process of collection and analysis of data and delve into the process of writing and theorisation. Finally, I discuss the ethical considerations concerning the risks to participants, the approaches to obtain consent, and some reflections about my positionality during the conduct of fieldwork.

Arriving at the research questions

The research journey started with an interest in exploring the ways in which people experiment with emerging hardware development platforms, some of which eventually lead to innovations such as IoT artefacts and applications. I set out to explore the practices associated with hardware development with different local groups in the UK, such as hackerspaces, hardware development forums and start-up events, which quickly unwound questions about a broader and highly contested landscape in the emerging internet of things industry. I was confronted with an astoundingly complex battleground of platforms, vendors, standard developers and competing international industrial and regulatory agendas. Early in my interaction with developers working in various business domains, I realised that their efforts were not confined to the development of physical objects, but that a considerable amount of network deployment, integration and adaptation between different systems was taking place. What later surfaced in the course of the initial exploration, was that internet of things applications permeate a diversity of domains of expertise, actors and organisations, and that unpacking that diversity of work would be a viable point of entry to such a complex landscape. At this point, I expanded the initial scope of the research to take into account the development and implementation of the underlying networks that support the operation of connected objects.

Some of the projects I considered at this stage leveraged the then-nascent low-power and long-range wireless standards for connected devices and the relatively low cost of hardware and software development tools. As my interest centred on the unpacking the involvement of different actors in technology development I narrowed down my options to two organisations competing in an emerging battleground of low-power networks: A French firm deploying a proprietary network with venture capital and a strategy oriented to business incubation (Sigfox), and a non-profit organisation based in Amsterdam seeking to crowdsource network infrastructure in a volunteer basis ('The Things Network'). Although I contacted both organisations to assess the feasibility of the research and both comprised promissory sites of inquiry, I ultimately chose to focus only on one case. The first option offered a more conventional vertical approach where infrastructure work was organised by an internal engineering division while the development of products and business incubation was handled by an outward-facing unit. In contrast, The Things Network initiative (hereafter TTN) sought to build a decentralised internet of things network by departing from the traditional *modus operandi* of the industry. At the time, the feasibility of the model was surrounded by much uncertainty, so its proponents were highly amenable to the aims of the research. After considering the practical implications of negotiating access and conducting an ethnographic exploration, I opted for the latter option.

The ensuing proposal was a qualitative exploration of the processes of inception and early scaling up a new global internet of things data network throughout its early years of existence. In this context, the study is concerned with the following questions:

1. What are the types of technical work, social organisations and technological offerings produced within TTN ecosystem?
2. What are the factors influencing the decisions to initiate and operate local TTN networks, and what are the mechanisms for aligning and coordinating work between geographically dispersed actors?
3. To what extent are coordinators able to steer the scaling-up and trajectory of the TTN initiative at local, regional and global levels, and what are the specific strategic decisions aimed at succeeding in this endeavour?

4. How do dispersed forms of work lead to the production of innovations and stable networks?

Although these questions bear the original motivation of this research, they have been reworked from previous formulations as I delineated the research design. The first three questions are motivated by the interest in shedding light on a new empirical domain while the last question calls for a theorisation of the processes of innovation in decentralised infrastructures. In Table 1, I map out how each of the research questions is addressed throughout three empirical chapters.

Table 2: Research questions and empirical chapters

Research question	*Methods and strategy*	*Chapters*
RQ1	A detailed sociotechnical account of the TTN ecosystem is outlined in Chapter 5. I address this question by tracing the stages of conception, implementation and scale-up of the initiative and outline a taxonomy of practices, artefacts and social organisations subsumed in the initiative	5
RQ2	This question is tackled in Chapter 6, where I outline the range of different motivations deriving from my informants' responses. I then propose a conceptual framework to explain how tensions and dilemmas between disparate agendas are resolved.	6
RQ3	Deriving from the previous analysis, I problematise the issue of control in the context of complex systems, and I assess the effectiveness of the decisions made my coordinators.	6
RQ4	I address this question in Chapter 7, where I delve into the production of applications, products and solutions on top of IoT networks and analyse the implications of distributed models of work for innovation. To do this, I schematise the division of responsibilities within the initiative and identify their specific contributions to the production of IoT offerings.	7

Research paradigm

As discussed in the previous chapter, this research builds on a social-constructivist epistemology. Within the constructivist/interpretivist paradigm, social phenomena are accessed through the discursive representations of informants, and in this way, theories are developed from the way social actors understand their world (Blaikie, 2009). Hence, the central approach for this study entailed a close engagement with the research field aimed at gathering such representations in relation to the research questions. The research design followed an iterative and adaptive process. As fieldwork unfolded and more data became available, subsequent components of the research design (i.e. the content of interview questions, the choice or secondary sources, the conduct and means of data collection and the sampling of sites and informants) were adjusted accordingly.

The abductive logic of inquiry is conducive to an interpretivist research paradigm insofar as theory is crafted through recursive validation in the field and broad consideration of existing theories and concepts (Timmermans and Tavory, 2012). In other words, new hypotheses, typologies and concepts are conjectured through a series of checks and improvements with the help of informants. Nonetheless, in contrast with the purely inductive approach of grounded theory, existing concepts and theories are taken into account as they may explicate, at least to some extent, the observed phenomena or instead, flag the need for expansion or crafting of new theory. Some of the theoretical contributions of this thesis are in fact expressed in terms of what are the limits of existing concepts and how they shall be refined or replaced in order to appeal to generalisation. This approach is particularly helpful to study emerging phenomena as it allows a space for conceptual and methodological creativity (Tavory, 2014). Abduction is rarely explicitly invoked in STS as an approach to theorisation, yet a combination of provisional and incremental analytical exegesis and methodological experimentation have been recurrently deployed in the field. In this study, I have applied the abductive logic to guide the process of interpretation and theorisation (I discuss this process further in the data analysis section).

Research Strategy

Case study: rationale and delimitation

Case studies have been widely used for the study of emerging phenomena as they are amenable to exploratory, descriptive and explanatory aims (Yin, 2003). Albeit often portrayed as a freestanding research design, they are but a method for demarcating and constructing the field of study (Blaikie and Priest, 2019). Quite tellingly, case studies have been a hallmark of STS research due to their effectiveness in uncovering the intricacies of scientific and technical practice, but also to their potential to 'evoke, illustrate, disrupt, instruct, and help STS to craft and recraft its theory' (Law, 2016, p.

32). The study of technological change has largely relied on case studies –some of them now emblematic—that have positioned this approach as a productive method for conceptual work (Monteiro, 1998; see e.g. de Laet and Mol, 2000; Karasti and Syrjänen, 2004; Pollock and Williams, 2009). The STS case study aims to a build a detailed exploration of an entire world and in that sense it is different from case studies used in business schools and economics.

Case studies in STS have nonetheless attracted criticism over their rationale for generalisation. In STS, the case study strategy tends to blend conceptual and empirical work through either building new theory on the basis of specific empirical contexts or interpreting new empirical material through the application of existing theories (Gad and Ribes, 2014). On the one hand, complaints have been raised about the rather pedagogical nature of case studies when these are used to explain established concepts and theories instead of substantively adding to the existing body of theory (Jensen, 2014). But more pointedly, some critics have expressed their discomfort with the limited usefulness of case studies for theory and for explaining circumstances other than their own and instead call for a methodological diversification in the field[12] (Geels, 2007; Wyatt and Balmer, 2007).

While these concerns flag a problematic epistemic relation between specificity and universality in STS, they also help to reinvigorate the value the case studies not merely as illustrative of their own specificity but for the construction of narratives that serve, if only, as building blocks of 'grand theories'. Through establishing connections between different cases, locales, circumstances, methodologies, disciplines, it has been possible to make broader claims by locating theory in the so-called 'middle-range' (Wyatt and Balmer, 2007). Such a framing is inspired in Robert Merton's idea of 'theories of the middle-range' which 'lie between the minor but necessary working hypotheses that evolve in abundance during day-to-day research and the all-inclusive systematic efforts to develop a unified theory that will explain all the observed uniformities of social behavior, social organization and social change' (Merton, 1968, p. 38). Moreover, the in-depth investigation of a phenomenon not only has the

[12] These authors have engaged in a programmatic debate in STS about the methodological direction of the field, some of the cited texts are part of two special issues in Science, Technology & Human Values: 'Middle-Range Theories in Science and Technology Studies' (2007) and 'The Conceptual and the Empirical - expanding STS' (2014)

potential to contribute to middle range theorisation in Mertonian terms but to enable experimentation with concepts between multiple sites and establish dialogues with other spheres such as research participants and policymakers (Hine, 2007).

In line with the epistemic debates, the selection of a case also reflects the intellectual interests and aspirations of the researcher. Indeed, a prime motivation for the choice of case for this thesis has been to open an idiosyncratic empirical domain to scrutiny and to build explanations for puzzling phenomena. Unpacking the empirical domain could offer opportunities to inform practitioners and policymakers, and as a result of the analysis and reflexive engagement with findings, theoretical and methodological implications become apparent.

The Things Network initiative

As mentioned earlier, the early steps in this research involved a process of exploration, background research and interactions with different industry actors in the internet of things. In this assessment, the TTN initiative was not only appealing for studying alternative modes of collaboration, but its exceptionality offered an opportunity for practical, analytical and methodological comparison with more typical cases (Seale, 1999). Following the evolution of a global data network called for spatial, temporal and institutional considerations for constructing the case study. In devising a research design, it seemed crucial to access different geographical contexts, social formations and stages of development.

Taking an organisational view as a point of departure, I defined the first unit of analysis as the overarching organisation coordinating the project. From its central position, this entity liaised on different fronts with a range of external actors such as communities of contributors or local initiatives, vendors, manufacturers and standard bodies. Within this broad landscape, I restricted the research to the scope of influence of core-developers and direct contributors to the initiative. Local contributors partake in the initiative in various ways through network implementation, business development, community engagement, application development, training, experimentation and other activities. I thus defined the second unit of analysis as comprised by the group of 'satellite' initiatives dispersed around the world. As shown in Figure 1, the result was a single-case study with two units of analysis (Yin, 2003). Later in this chapter, I discuss how data associated with both units of analysis was collected by different means and from a diversity of virtual and physical sites. Regarding timeframe, although I engaged directly with the initiative during a period of almost three years (32 months), the analysis incorporated archival data going back to 2015, which resulted in an overall timeframe of four years. For the sake of analysis, I divided this period into three phases: bootstrapping, initial expansion and scaling up (see Chapter 4).

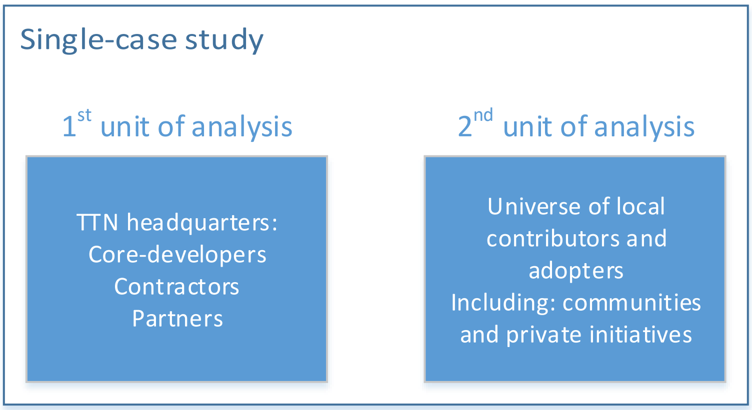

Figure 1: Case study space and units of analysis

Locating low-power networks in the landscape of the 'IoT'

The internet of things, albeit convenient as an all-encompassing technological trend, is particularly problematic from the ethnographic point of view. While in its most generic use, it describes any sort of physical object connected to the internet, at closer inspection, one encounters an array of different technical configurations and overlapping with more 'conventional' manifestations of the internet as well as future as-yet unrealised visions. While the most mundane IoT devices (e.g. smartphones) rely on existing internet connectivity, other, perhaps less obvious, objects such as sensors demand specific technical requirements where existing technologies fall short. Some differentiation in terminology have been made to capture the distinct types of IoTs (e.g. industrial IoT), yet it seems unproductive to ascribe to any of them here.

At this stage, it is necessary to give some caveats in regard to the use of the term 'internet of things' throughout the empirical chapters. I shall thus outline a brief overview of low-power networks as a boundary drawing exercise to delimitate the empirical focus of this study. Looking at communication standards is a helpful way to locate the case of TTN within the complex landscape of IoT. Figure 2 shows a map of wireless technologies in terms of their bandwidth and range (Mekki *et al.*, 2019). At the lower end of these axes, lie short-range and low capacity technologies such as RFID and NFC, used for passive tagging of objects for monitoring and tracking, access control and contactless transactions. In the middle region of the map are legacy wireless and mobile technologies. Much of the new IoT infrastructure derives as a natural extension of existing mobile technologies while incumbent telecom operators transition into 5G networks. These networks cater for applications with high demands of bandwidth and coverage, which are commonly used by consumer products. Lastly, a subset of wireless communication standards bundled up under the rubric of 'Low Power Wide Area Networks' (LPWANs) has emerged in the last decade to fulfil two key requirements of sensor networks, namely low power demands paired with long-range connectivity. Sensor networks have applicability in various domains including, for example, asset tracking, smart meters, environmental monitoring and smart agriculture.

It is within the space of low-power wireless networks that TTN operates. Unless stated explicitly, I shall use the term 'internet of things' throughout the analysis to refer more specifically to low-power networks rather than to the whole spectrum of application of the term.

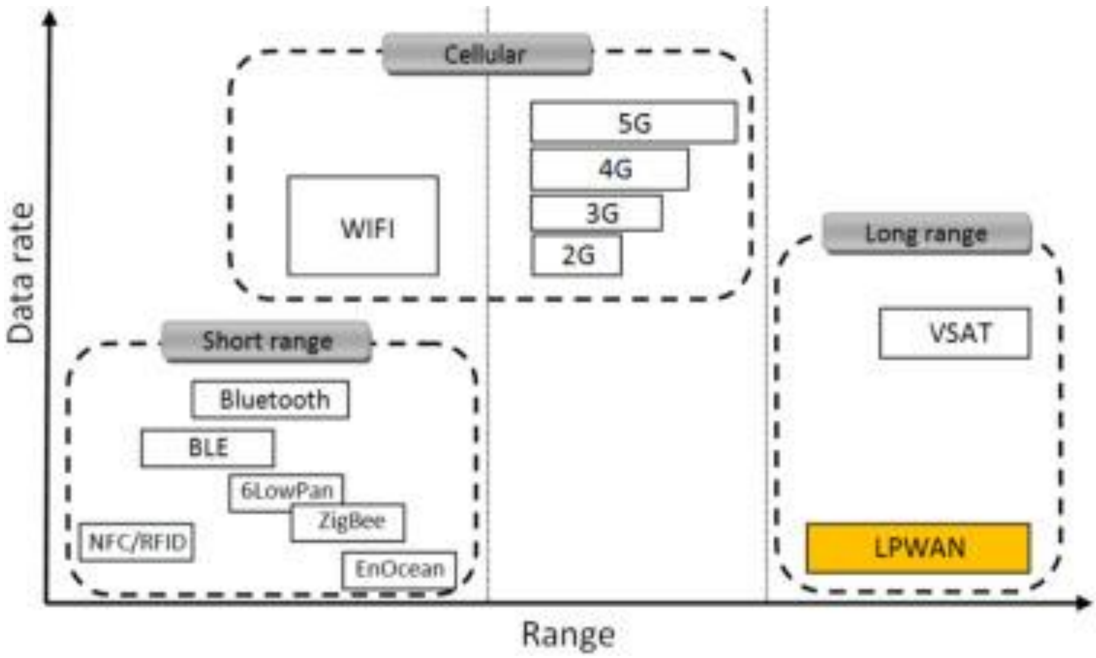

Figure 2: Data rate vs range of wireless communication technologies (reprinted from Mekki et al.*, 2019)*

An ethnography of dispersed infrastructure work

In tandem with case studies, the in-depth exploration of social phenomena has galvanised much work in science and technology studies. Most notably, longitudinal ethnographic studies have been proposed as alternatives to macro-economic and macro-sociological accounts and have quite successfully helped to build rich accounts of the everyday work of scientists and engineers (Knorr-Cetina and Bruegger, 1981; Latour and Woolgar, 1986; Latour, 1987). The ethnographic observation of 'invisible' work practices has been a helpful method to arrive at nuanced accounts about the use of systems, and to uncover unexpected situations showing for example that 'people did not usually use the systems for the designed purposes' (Star and Strauss, 1999, p. 26).

More recently, work on information infrastructures has shown a renewed interest in examining new forms of work practices by moving beyond traditional single-site ethnographies and taking into account the interlinked and distributed nature of work through observing online and offline interactions (Jackson *et al.*, 2007; Edwards *et al.*, 2009; Pollock *et al.*, 2009; Tsing, 2011; Williams and Pollock, 2012). This impetus resonates with efforts to access the global scale by examining the connections between multiple local sites (Marcus, 1995; Hine, 2007). In order to build explanations about how facts and artefacts are constructed, this type of ethnographic work calls for a close observation and detailed description of the everyday practices of participants and a linking up between multiple sites.

While multi-site ethnographies appeal to a generality beyond their own contexts, their purpose is not to produce holistic accounts that are akin to the ambitions of macro studies. To cite George Marcus (1995, p. 99):

> [...] the multi-sited ethnography is content to stipulate some sort of total world system as long as the terms of any particular macro-construct of that system are not allowed to stand for the context of ethnographic work that becomes opportunistically constituted by the path or trajectory it takes in its design of sites.

At a practical level, the construction of the ethnographic terrain entails a balancing act between detail, variability and feasibility. Particularly in the context of time-constrained research projects, extended studies may prove to be highly strenuous if not unfeasible. In the study of infrastructures, noteworthy events during design, development and use may occur unpredictably in different locales and over long periods (from a few years to decades), rendering pure observation impractical for a doctoral research project. In light of these challenges, the ethnographic work for this study has been designed to be flexible by incorporating different strategies, sources and additional material.

Inspired in its use in anthropology, I apply the term 'ethnography'[13] as shorthand for a set of different methods and tactics for accessing the world of software and hardware developers, community initiators, managers, network implementers, business developers and researchers. Whilst a significant part of my fieldwork involved observing and recording fieldnotes about everyday practices, I dedicated a great deal of time to partaking in technical activities and engaging in informal conversations with a wide range of people. I conducted 'face-to-face' participant observations at different sites including The Things Network headquarters, technical workshops, community meetups and conferences. Additionally, I observed online channels consistently during the whole period of data collection, albeit more frequently in the early phases. This component was crucial throughout the research journey as it allowed me to maintain an up-to-date stream of information, find out about events, contact participants and conduct interviews.

In their article *Studying infrastructuring ethnographically*, Karasti and Blomberg (2018) argue that the ethnographer is compelled to demarcate the boundaries of the field as new circumstances emerge. This warning is rooted in the fact that researchers are necessarily in continuous relation with their object of study, altering the social reality and making conscious decisions as to what to include and what to leave out. This falls in line with the need for being reflexive in the practice of ethnography, making epistemological commitments visible and avoiding claims of objective and holistic accounts of reality (Brewer, 2000). In this sense, my process of boundary making entailed a continuous evaluation of the (online and offline) 'sites'[14] included in the ethnographic enquiry.

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[13] In this thesis the term 'fieldwork' is also frequently used in lieu of ethnography

[14] The 'internet-as-space' metaphor is in itself a way to grapple with constructing boundaries around digital material and online sources. Indeed, alternative formulations such as 'internet as virtual' or 'as text' have been adopted elsewhere depending on the research conditions (see Bassett and O'Riordan, 2002).

In the selection of sites, I considered the specific circumstances of the research such as timing, accessibility, relevance and availability of data. Conjointly, I continuously contrasted and validated my interpretations through conversations and other forms of intervention, as opposed to attempting to produce detached and objective descriptions (Hine, 2007). Restating the abductive approach, I privileged serendipity and encounters with the unexpected during fieldwork: even though a rough itinerary was devised at the outset, the sample of communities and relevant/observable sites of action was ultimately constructed as the fieldwork unfolded. This strategy was not only useful to grapple with the unknown but to adapt to the changing circumstances of the field.

Navigating through participation and observation

Considering this is a field which is still in construction, where much trial and error takes place and where future visions are continuously changing, there was a need to strike a balance between the timeframe of the study and the variability of data. Particularly early in the study, the 'global' scale appeared more as an aspiration shaped by the initiative coordinators rather than an actual space of enquiry. This ambivalence posed a challenge of formulating a research design around both concrete as well as promissory objects. During fieldwork, I was indeed confronted both with sites where networks were operating, and more data was available as well as with projected sites with scattered observational data. The emerging research design was therefore primarily centred on several *operational* sites partaking with the initiative throughout a feasible observation period.

In total, fieldwork spanned over two and a half years (from February 2017 until October 2019) comprising a combination of face-to-face participant observation at TTN headquarters, visits to communities and key events and observation of online interactions. During this time, I positioned myself as both 'passive observer' and 'participant as observer' (McNeill, 2005), seeking consent and making my goals clear to participants[15]. Engaging with the core team onsite allowed me not only to build a

[15] I sought informed consent in advance from TTN through circulating an organisational consent form and a research information sheet in internal channels. Additionally, I verbally discussed the reasons of my presence with participants. However, individual consent and disclosure were not sought at all times due to practical reasons (e.g. in public forums or highly attended online events), and to prevent causing unease on participants.

notion of the internal processes of technical development and strategic decision making but also to identify key informants and guide the line of questioning of interviews. My observations focused on the work carried out by TTN staff as well as by external partners and contributors. Regardless of my existing knowledge, I adopted the role of 'acceptable incompetent' (Fielding, 2015): I exploited my position as 'new to the culture' to elicit basic explanations about new topics from team members and create opportunities for engagement. Nonetheless, my prior training in electronics engineering put me in an advantageous for observation as it allowed me to dig deeper in conversations and empathise with my informants (some of them engineers).

The wealth of educational material and tools opened a space of learning for anyone with an interest, which included me in my role as a social scientist. Particularly during the first year of fieldwork, I partook in technical workshops, training courses, hackathons, peer-to-peer support and self-guided experimentation around emerging sensor networks and IoT technologies. These activities were not only highly rewarding but allowed me to gain technical insight, update my vocabulary, pose relevant questions and most importantly build rapport with my informants. Informational talks about community organisation and technical workshops facilitated by community managers and experienced peer members were recurring events throughout my involvement. They constituted ideal settings for sparking informal conversations and for getting to grips with the technology and technical jargon which was prevalent across all circles. Although the familiarity with technical practice and terminology was a necessary by-product of the research, I consistently engaged with formative groundwork in order to establish a common language. Conversely, I was occasionally compelled to give explanations or eschew exotic scholarly terms from the social sciences

A challenge for the research design was the rather dispersed nature of technical work. In light of the impracticability of travelling to multiple sites, I chose to follow the traces of work through online channels which offered not only a rich source of data but a means to reach informants directly. This was an important consideration for the construction of the field as it flagged a need to comprehend not only physical spaces but 'virtual spaces' (Beaulieu, 2004). After spending a period with the core-team in Amsterdam, the focus expanded to incorporate the work of external contributors. From this point onwards (until the closure of data collection), I used a combination of online observations and field trips to access informants more efficiently and to mitigate the constraints of time and resources.

For the task of online observation, I focused on two prime online media, namely a public Slack workspace[16] and a web-based discussion forum. Both media comprised spaces for interaction between members, notably for technical peer-to-peer support and for dealing with pressing issues in real-time. Rather than framing this stage as a comprehensive ethnography of online interactions, my observation centred on *following the traces of work* and *following the problems*. In other words, I focused on how collaboration tools were used to accomplish daily tasks, dealing with technical and organisational problems, learning and adapting the technology locally or exposing and negotiating disparate visions and agendas. Through observing these aspects of online interactions, I sought to build an account of the *material* work and struggles of developers, and the different strategies they deployed to deal with them. This form of observation resembles what Christine Hine has called 'virtual ethnography' (Hine, 2000, 2008).

Incorporating peripheral views

Participant observation was insufficient on its own owing not only to the unfeasibility of travelling to a large enough sample of remote locations but to the nature of the different local assemblages. The term 'community' was part of the vocabulary used by TTN to refer to local instantiations of the initiative regardless of their size and number of members. However, the majority of communities at the time of my enquiry were far from being coherent organisations. Even some of the more established communities did not maintain a permanent physical space or held regular face-to-face meetings in a way that would be conducive to conventional forms of participant observation. Therefore, semi-structured interviews helped more efficiently to access the world of local groups through the voices of their members.

In tandem with observations, interviews are an excellent way to gather overlooked or hidden information, challenge taken-for-granted assumptions, involve underrepresented actors, reconstruct the past through personal histories and guide

[16] Internal and external members routinely used this real-time collaboration tool with separate private and public-facing workspaces

further data collection (Brewer, 2000). In this case, although personal accounts were not always representative of the diversity of local contributors, they provided crucial insights about the histories, current affairs and future outlook of local communities. The purpose of interviews, in this case, was to obtain a broad picture of the work practices, social dynamics and forms of organisation taking place at the local level. Rather than aiming for a representative sample of the universe of communities, I primarily interviewed members of the so-called 'mature' communities[17].

Early during the fieldwork, the number of mature communities was significantly higher in Europe than in other regions. In turn, incipient communities elsewhere had a small number of members, minimal or no infrastructure and an uncertain future, which made them less appealing for pursuing interviews. Although this is a finding in itself, it also supposed a methodological limitation which resulted in a Eurocentric view of the case. In the analysis, I moderated this shortcoming by means of methodological triangulation (Denzin and Lincoln, 2013) with other sources of data such as 'leads' from informants, forum threads and global statistics.

In order to cover a diverse range of geographically dispersed communities and mitigate the costs of travel, the majority of interviews were conducted online (via Skype or Slack). Recruiting participants without personally meeting them first was a difficult and often unfruitful task requiring several attempts and different tactics. Due to the fact that most external contributors had full-time jobs and busy schedules beyond their involvement with TTN, introducing myself virtually, did not always lead to a successful outcome. Hence, during the early stages, I leveraged my direct contact with gatekeepers (in this case community managers), who were happy to do introductions and 'vouch' for the legitimacy of the interviews. Additionally, I relied on a combination of tactics such as recruiting interviewees at events or via the Slack real-time channels.

[17] As I will show in Chapter 5, TTN community managers measured the relative maturity of communities in terms of the existing infrastructure and number of members. However, as these criteria were not always reliable, I also relied on contrasting information directly with my informants.

The process of data collection

Gaining access

Before selecting the case and establishing the first contact with my informants, I conducted substantial preliminary work. As mentioned at the start of this chapter, I gathered background information about TTN as well as other competing organisations through attending events and examining publicly available information on the web including media articles, blog posts and online documents. In October 2016, I emailed Wienke Giezeman, one of the founders of TTN, with a lay summary of the research and a request to visit their facilities in Amsterdam for a short-term participant observation. I was then invited to a conference call where I outlined my proposal for joining the organisation as a self-funded volunteer in order to conduct a qualitative study. Giezeman welcomed the idea and subsequently introduced me to the team of community managers which he deemed well-positioned to guide my forays into the organisation. From this point, until the start of my visit, I maintained regular communication with the two community managers via phone calls and emails to negotiate a plan of action. At this stage, I was invited to join the organisation's internal Slack workspace, where I introduced myself virtually to other members of the TTN team. Eventually, an initial three-months visit to the headquarters was agreed[18]. Based on this arrangement, I wrote a proposal for consideration by the University of Edinburgh first year review board, which approved the commencement of fieldwork. Upon compliance with the University of Edinburgh research ethics and fieldwork travel risk procedures, I set out to start my visit to the TTN headquarters in February 2017.

Conducting online and 'offline' observations

An immersion with core developers

Early during fieldwork, I 'shadowed' the two community managers and held meetings with a newly created team named 'value exchange' which was in charge of experimenting with enforcing fair use of the network. In this manner, I was able to get

[18] Although a longer period would have been preferable, I was confronted with visa limitations which caused a significant hurdle in terms of mobility throughout fieldwork.

a sense of both the outward-facing relationship with communities and the internal processes. I focused on noteworthy interactions and events and started by recording the layout of the workplace, the division of tasks and daily routines such as stand-up meetings –a common ritual within software development teams. I endeavoured to write down as much detail as possible, including contextual information, names, drawings and diagrams. While I made efforts to interact with all members of the team without intruding in their activities, this was especially challenging with software developers due to the fact that they were not accustomed to discussing their work with someone unfamiliar with the process. Unsurprisingly, a substantial amount of their time was devoted to computer-based work which was not readily evident or graspable solely through direct observation. Tasks such as front-end and back-end coding, debugging, curating open source code, moderating online channels, creating documentation and content, researching, and computer-mediated communication, would have been largely glossed over without the use of observation-aiding tools and creative means to capture them more adequately.

The Slack interface rendered computer-based activities fairly 'observable' and constituted a routine instrument for data collection. Indeed, quite advantageously for my own notetaking practice was the fact that before daily stand-up meetings all members of the team wrote briefings of their work on Slack which included short descriptions of their duties (Figure 3). In tandem with the daily practice of Slack-based observation, I endeavoured to trigger face-to-face discussions in the workplace. Smoke breaks, lunch breaks, meetings and informal gatherings offered invaluable opportunities to ask pressing questions and to build rapport with the core developers.

```
Dev1 [12:43 AM]
Probably missing standup
*yesterday* influx storage, tests, working around some issues with it
*today* off

CM [8:27 AM]
Will miss stand up as well

*Yesterday* hand in conference paper, editing webinar
*Today* activate ALab gateway, KS update, meeting ** activity feed, call Utrecht community

Dev2 [8:36 AM]
Yesterday: tests code cleanup and began to implement a healthcheck
Today: healthcheck, sync with **

BD1 [8:59 AM]
*yesterday* MIRAIT call, OCTONET call + proposal work
*today*Accenture next steps, VerticalM2M, Eneco, SIDN BLockchain call, Planon call, Interoperable
modular gateway call, Sync ** on leads, meeting Russian guys

BD2 [9:02 AM]
Yesterday: Mirait call, 3 potential hires call, call tweetonig, call H2020 potetial call, meeting with
Tokyo Power
[9:03]
Today:  call with Digikey, meeting with some random Russian, new hires, meeting with Eneco

TL [9:05 AM]
*Yesterday* discussed provisioning and app for E&A in Barneveld, followed up with mails, HR call, code
reviews
*Today* HR call, Accenture preps and meeting, sync with ** and **, two more calls, fix myDevices'
gateway
```

Figure 3: Excerpt from a stand-up meeting log (March 2017)

Accessing local contributors

I followed local contributors both through online channels and during my field trips to community events. While Slack provided a good vantage point to observe public posts and replies passively and in real-time, I also used its interactive functions to initiate and partake in discussions. The public Slack workspace contained various thematic channels moderated both by core-members and by contributors. Threads and posts populated different channels and were organised through the use of hashtags (Figure 4). Channels varied in popularity depending on the topic and on whether they were only relevant for a particular group, for instance, within a particular city or country. While I focused on the most active and subscribed channels (e.g. #general, #support, #hardware, #backend, #lorawan, #website), I also joined several active local channels and a separate Slack workspace used by a large number of members based in Switzerland.

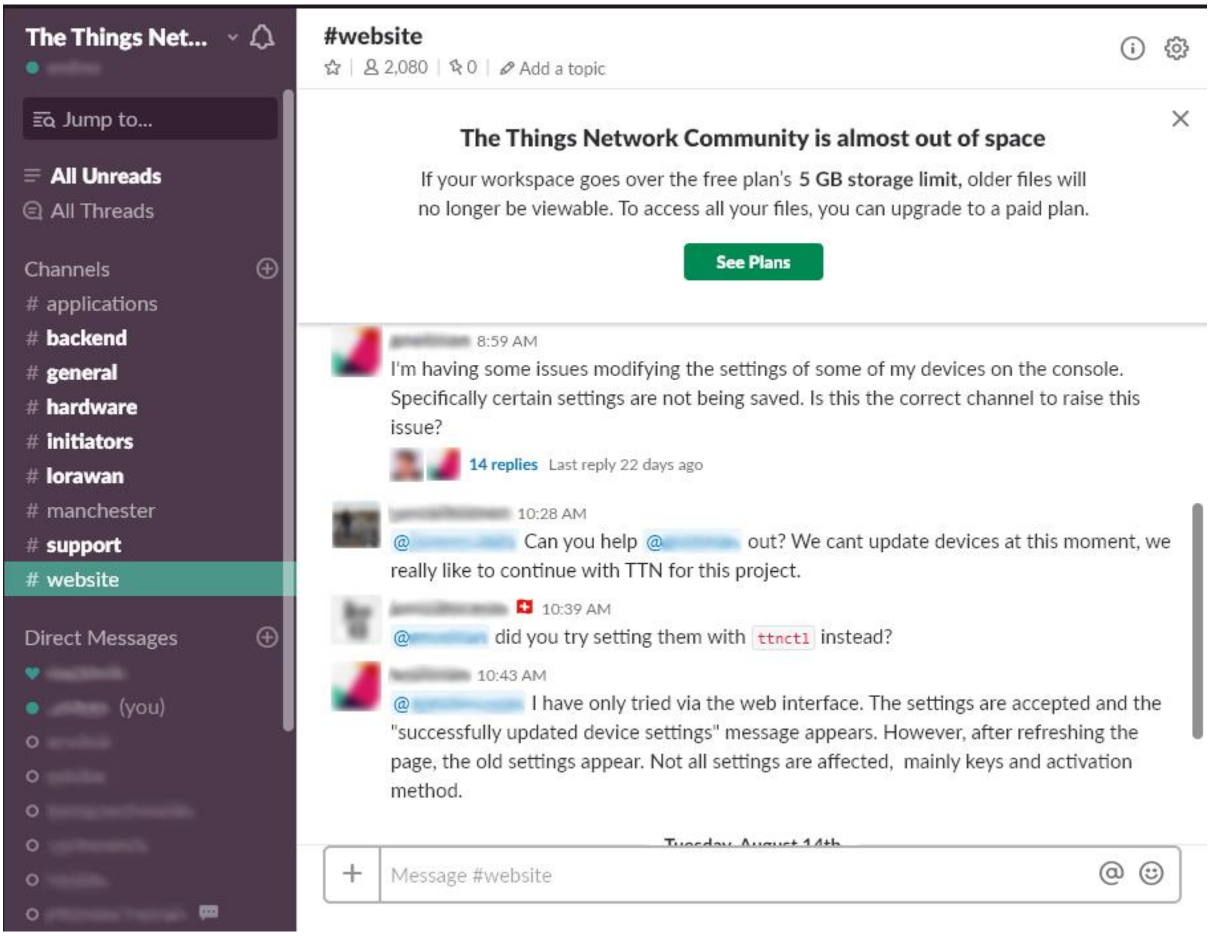

Figure 4: Slack interface (August 2018)

In parallel, I regularly monitored the online forum (Figure 5), which also contained thematic threads populated and moderated organically by users. In contrast with Slack, the forum holds a permanent and public log of discussions. Due to the format of the forum, discussions took placed at a slower pace, extending over longer timescales (sometimes spanning years) and covering a technical as well as more philosophical subjects. This resource could also be seen as a text-based source, or a document archive rather than a real-time interactional space.

I examined the two media in tandem and exploited the indexability of text to sort through and analyse the data. Both media subsumed a high number of users[19], albeit only a fraction of them participated actively in creating content and participating in discussions. In this case, core developers, forum moderators and other influential members were consistently visible on these spaces. I made local copies and

[19] According to the metrics obtained from these channels, the number of active online users fluctuated around 15000 on the online forum and 5000 on Slack during my involvement.

screenshots of relevant discussion threads from Slack and the forum and wrote 'side notes' which included provisional reflections, patterns of use and relevant contextual information. The primary technique of observation entailed the identification of salient problems or struggles which I used as a means to trace instances of learning, aligning and negotiating. At the same time, the focus on problems served as a proxy of the work carried out by local contributors. Users of the forum and Slack channel not only directly addressed core-developers with questions but frequently discussed issues with commissioning equipment, installing gateways, recruiting members, organising legal structures.

These sites were used intensively to share knowledge and experiences and for peer-to-peer support. My observation thus consisted of engaging with these discussions and writing contextual notes about common issues experienced by contributors and the way they were resolved. These observation activities offered a great deal of insight into the work of local actors, yet they were tasks with diminishing returns. During the first stages of fieldwork, I observed Slack-based online interactions on a daily basis which was gradually scaled down to an average of one observation per week during the latest stages. The forum offered a more dynamic space given its more permanent status and therefore observations of forum threads were contingent to how they were populated by users.

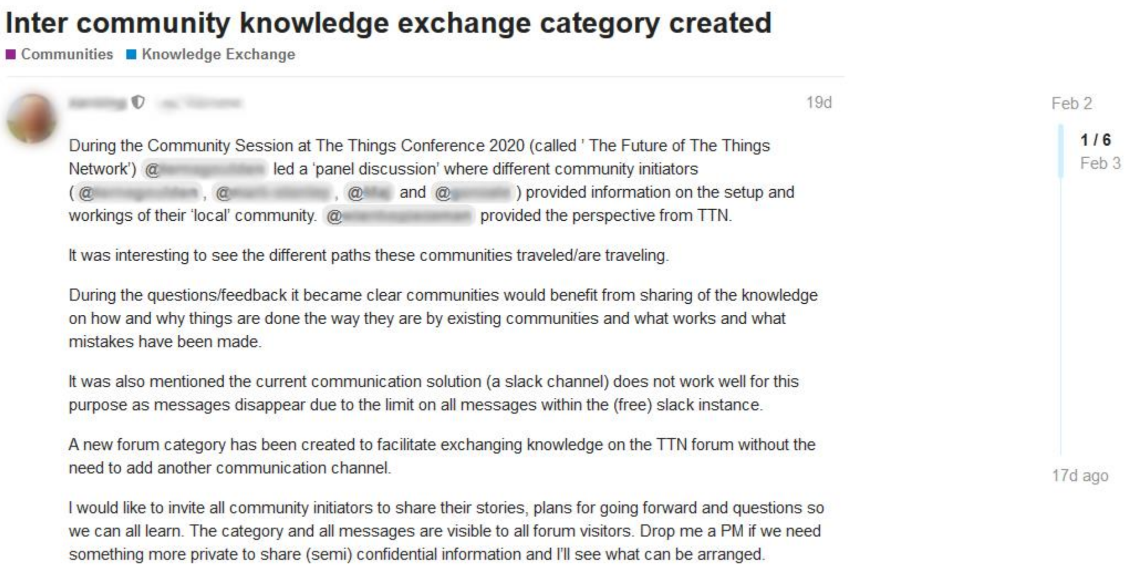

Figure 5: Sample forum entry (February 2020)

Work with hardware and physical infrastructure involved a combination of manual work and computer-based work, and therefore, registering its complexity benefited from a degree of familiarity with technical practices. Moreover, much of this work was either conducted outdoors or at experimental and pedagogic settings, which required observations to take place in a rather opportunistic way. I organised several trips to a range of events including community meetups, technical workshops, hackathons, industry events, conferences and summits, makerspaces, labs and hackerspaces. My intention in these events was to partake whenever possible as 'just another participant' and establish relationships that would point me to further field trips or interviews. My strategy was to engage in conversations (some of them extended over an hour) about technical processes, local organisation and pressing challenges. Fieldtrips also provided me with an outlook of the state-of-the-art. During industry events and workshops, I gained privileged access to new applications, use cases, communities, tools. I recorded notes and insights of my participation on events and built a digital archive of material including slides, videos, photographs and documents.

Although it became second nature to write notes during talks and presentations, the hands-on format of certain events made immediate notetaking impractical. In those circumstances, I either 'retreated' to write down notes or ensured to recollect events at the end of the day while they were still fresh in my memory. Writing notes on my laptop rather than on paper offered an ideal form of retreat, particularly during workshops.

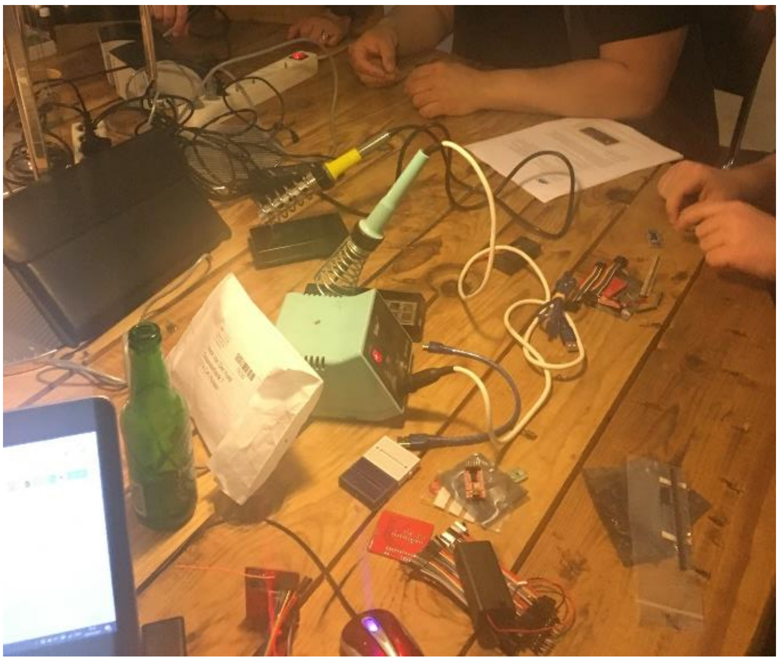

Figure 6: A hands-on hardware workshop (March 2017)

Semi-structured interviews

Semi-structured interviews comprised the main instrument for accessing the world of local communities and for compensating for the time constraints and costs of participant observation. During and after my immersion in Amsterdam, I gathered data about various communities through the views of different external actors. In collaboration with the community managers, I curated a list of interview candidates based on their influential role and the relevance of their particular location. In total, I interviewed 20 participants, including initiators, core members, academics and implementers (see Appendix I). The majority of interviewees (16) were directly involved with a local community, while 2 of them operated more autonomously. I conducted follow up interviews with the founders of TTN towards the closure of data collection. Interviews typically lasted from 60 to 90 minutes. Two interviews were conducted in Spanish and the rest in English. All but one interviewee were men.

To guide the conduct of the interviews, I designed a schedule with questions covering the following themes: community history and composition, individual and collective motivations, governance, quality of service, projects and applications, users, funding and sustainability (see Appendix II). Whilst I kept a flexible format allowing for occasional detours and emerging themes to be pursued, I also made attempts to avoid straying too far into technical elaborations by reframing the questions or aligning back to the schedule. Brewer (2000) notes that a common drawback with interviews is the tendency of informants to favour positive accounts (or to downplay problems) due to the so-called ‘interviewer effect’ or in order to promote the initiative to outsiders. To moderate this issue, I emphasised on specific questions or sought elaborations on apparent challenges and problems. Still, it was not unusual to hear from interviewees about frustrations, struggles and forceful critiques to the overall initiative.

I produced full interview transcripts from the first round of interviews in order to conduct interim analyses and adjust my strategy accordingly. As a result, subsequent interviews were revised and slightly changed in style and content. Whenever appropriate, I incorporated additional questions about the evolution of the community in the last years and sought elaborations on emerging themes such as the conflicts between different visions, innovation processes and the future of the community.

Additional material

Throughout fieldwork, I routinely compiled several contemporary and retrospective documents and datasets of different sorts. These included news and academic articles, blog posts, webinars and online presentations, wiki entries, emails, technical documentation, code repositories, web screenshots, images, diagrams, meeting minutes, community profiles and longitudinal, global statistics. While most of the data is accessible in the public domain, some of the internal datasets and documents were obtained directly from my informants. To reconstruct earlier developments, I resourced to archives of documents going back to 2015. I collected monthly snapshots of the global statistics about registered gateways, cities and developers, which were published in real-time on the website. This data was useful to trace the trajectory of the initiative across temporal and spatial scales and triangulate with other sources of data to substantiate the analysis. Photographs and videos obtained during and after my interactions with informants helped to contextualise and 'refresh' the evidence at later stages. The corpus of complementary material comprised a helpful resource to produce a rounded picture of the case.

Data analysis

In this section, I delve into the process of articulating a narrative and constructing meaning out of the large volume of material. Rather than using a process of isolated theory-crafting from the data, I endeavoured to recurrently check and validate my preliminary interpretations and speculations in the field as well as in various academic settings. Having delineated a theoretical framework, the process of analysis entailed a continuous validation of my interpretations in the field and a sensibility with existing theoretical concepts from the literature. This approach meant that moments of analysis needed to be conducted in parallel with moments of data collection. While I conducted a more systematic process of analysis after the formal conclusion of data collection, I routinely engaged with data structuring and interim analysis in the midst of fieldwork. I routinely sorted and organised portions of the data and kept a collection of side notes and reflections from the field under the label 'provisional findings'. As a regular practice, I contrasted my own views and guesses about the state of affairs with those of my informants. Rather than settling for conceptual fits and uncontroversial views, I found disagreements, puzzling debates and tensions between members of different or multiple groups deeply enriching for my own process of reflection. After my first immersion in the field, I produced various mind maps, relationship graphs and descriptive texts which were discussed at various stages with my supervisors and presented as work-in-progress at several academic conferences and workshops. Interim analyses importantly helped to adjust the focus of my observations and reformulate the line of questioning of further interviews in order to check interpretations with informants and include emerging themes. At a practical level, dealing with data at different stages throughout the research allowed me to avoid accruing unprocessed notes and recordings and to check against my fallible recollections from the field.

The process of analysis can be broadly distilled into the following three steps (Brewer, 2000): data reduction, data classification and display, and conclusion drawing.

Transcription and data reduction

To grapple with the large volume of data, I relied on NVivo and spreadsheets. Most of the qualitative data was collected digitally, which facilitated indexation, labelling, coding and visualisation via software. However, a remarkably arduous task was the transcription of interviews. To manage time and resources, I devised a semi-automated method combining speech recognition software with a python script to produce raw text files from audio recordings. This method reduced the transcription time to around 3 hours of edition per hour of recording, which was often carried out across a few days as time allowed. The overall process of transcription extended throughout almost the whole period of data collection with all but two interviews fully transcribed. This technique required me to listen to audio recordings in full, which was a useful way to relive my encounters and pick up on details that may have gone unnoticed during interviews. I incrementally input my fieldnotes and transcripts in an NVivo project in order to sort and manage the data using different parameters including source type, date and keywords. As an additional parameter, I created a list of 'cases' corresponding to the different institutions and communities connected with the TTN initiative. This process provided the first instance of familiarisation with the sheer size and the different sources of data. Additional material, however, was not systematised in the same way as field notes and transcripts due to the large number of documents and the variability of formats. Instead, these sources were consulted as the need arose for purposes of triangulation and argumentation.

Data classification and display

I conducted the first round of labelling and thematic coding by linking excerpts of text from interview transcripts and fieldnotes to themes. The codes emerged as I analysed each data source assigning them to concepts, interview questions and content categories found in the data (e.g. background, motivations, challenges, field of application, ethos, decentralisation). On NVivo, I ran queries using combinations of codes to generate visualisations which were helpful to identify recurring themes and patterns in the data. Hierarchy charts and word clouds, for example, revealed relationships between data sources and how certain codes were recurring or infrequent in field notes and interview transcripts. By experimenting with different queries, I built mind maps, diagrams and relationship networks to produce a general picture out of the data. In the second round of coding, I refined the list of themes by adding new keywords stemming from incoming data and revised and grouped existing ones into overarching categories (e.g. innovation, infrastructure, users).

Conclusion drawing

Constructing meaning out of the data entailed not only the inference of new concepts and models but a critique of existing ones that came about from identifying links and misfits between the literature and the empirical data (Timmermans and Tavory, 2012). Far from being a one-off moment of theorisation, this process involved a continued retreat and revisiting of the data as well as a sensitisation with relevant theory and comparable empirical cases. For instance, reviewing other studies of infrastructure and distributed work allowed me to locate empirical regularities. I aimed in this way to elucidate 'what the case is a case of?' and where it stands in terms of timing and boundaries (Ragin and Becker, 1992). Moreover, by *looking back* at the data, I incorporated temporality in the analysis in order to weave a coherent account of the case study. The act of writing was itself an inseparable part of the analysis as it allowed me to explore narratives, practice reflexivity and recast phenomena under different conceptual lenses. The writing period also overlapped with the late stages of data collection, which opened occasions for probing the argumentation. The resulting analysis, which I develop in the next three chapters, comprises a combination of empirical description, explanation drawing from the existing literature and elaboration of new concepts that explicate the case but also give general claims that go beyond the specificity of the context.

Ethical considerations

Due to the fact that this study focused on technical and organisational practices where no personal/sensitive data or vulnerable groups were purposely included, I did not encounter major ethical dilemmas. Nonetheless, some difficulties and risks were anticipated in connection with the proposed research design and also dealt with as they arose during as fieldwork unfolded. In this section, I discuss the various ethical challenges each part of the research posed and the way they were addressed. I also reflect on the risks and limitations that relate to my positionality in the practice of ethnographic research.

Obtaining informed consent

Prior to my formal immersion in the field, I conducted a research ethics assessment and a travel and fieldwork risk assessment in compliance with the University of Edinburgh regulations. At this stage, I foresaw the need to timely disclose the aims of the research with participants whenever possible, not only to minimise the risk of misunderstandings but to create a space of transparent discussion about the research, particularly at workplaces and face-to-face interactions. Conjointly, I endeavoured to obtain informed consent in a way that would not cause unnecessary anxieties on participants and contrived behaviours. At the outset of my stay in Amsterdam, I circulated a research summary among participants and obtained organisational consent for the study. Additionally, I ensured my role as a researcher was apparent to all members of the team (around 12 at the time) during verbal interactions, which was also the way to inform new members who joined the team after me. I did not take this approach in all settings due to circumstantial limitations and in order to avoid unduly causing disruptions or unease on participants. At events such as conferences, hackathons and workshops, rather than relying on forms, I opted for a more informal disclosure of the purposes of the research: during one-on-one or one-to-few interactions I introduced myself as a ‘social researcher’ to make sure, using plain language, that my research intentions were clear. This strategy proved to be effective in eschewing uncomfortable situations but also rewarding for the research as it frequently sparked relevant conversations.

Obtaining consent to conduct and record interviews was a straightforward and, to some extent, a streamlined process involving an exchange of documents (see Appendix III) and a brief discussion about the research before the start of the questions. Quite frequently, a critical aspect of securing interviews was the interest of participants in the study. While I offered to share my research findings upon completion, I refrained from making promises about the potential benefits or impact of the project, and no compensation was offered for their participation. Interviewees chose whether they wished to be quoted directly, anonymously with some identifying details or completely anonymously, and were reminded about their right to withdraw their participation at any moment. Not all of my informants agreed to be quoted directly and some participants asked to review the quotes if their names were to be used. Hence, I did not include names or additional details (e.g. position, affiliation or city) which could lead to identification through other means such as an online search.

Considerations about online observation

Compared to the ethical considerations of more traditional 'offline' methods, a new set of considerations arise when research is conducted online, particularly in regards to the practicalities of seeking informed consent (Eynon, Fry and Schroeder, 2008). During the observation of online interaction, it was not possible to disclose my status as a researcher at all times, due mainly to the rather casual nature of the use of both the online forum and Slack. Using written announcements or signposts, for instance, would have gone mostly unnoticed by occasional or new users or buried among the deluge of entries. Informed consent was therefore not obtained from the universe of online users but individually during direct communications. This decision was justified considering the observation of online channels did not focus on data about individual participants but the collective patterns of use and the overall content of discussions. Despite this, some risks call for cautious handling of the data to avoid harm coming to users. For one, the so-called 'public' Slack workspace was not open to the public at large, but to a relatively reduced group (a few thousands) of registered TTN users, and by default it did not hold a permanent log of data. Such a semi-private and ephemeral exposure of messages may influence the nature of the content: Slack users may, for instance, choose to share some personal and sensitive data or cover controversial topics openly in this environment. I mitigated this risk by anonymising names and avoiding disclosing evidently sensitive texts or personal details captured from this medium.

On the other hand, data obtained from the online forum is available in the public domain, containing a broad range of topics which generally did not flag a need to exclude this source in the study. The public availability of information, however, does not automatically legitimate its use for research purposes considering the potential misuse of data, particularly for large scale studies (Hughes, 2012). In this case, I made decisions on a case by case basis as to whether the content exhibited sensitive information that could compromise users' privacy and safety. Moreover, I did not make local copies of the entire forum for big-data analysis but instead made discrete searches of content directly on the *live* platform.

In general, the content of discussions in Slack and the forum did not call for an overly restrictive design which, in turn, could lead to problems of misrepresentation or partiality (Bassett and O'Riordan, 2002). Following good practice of information security and complying with the regulation on data protection (GDPR) were deemed adequate measures even when such provisions were not assessed by university procedures at the time. Regarding the storage of data, all field notes, recordings, transcripts and additional material have been stored in a local computer, and portions of the data have been shared with my supervisors.

Reflexivity and positionality

During my involvement, I performed different roles depending on the context switching from overt participant as observant, to passive observer and full participant. A very latent issue, particularly in the latter role, has been the well-known problem of ethnographers 'going native'. McNeill describes this problem as 'the possibility that the researcher will become over-involved with the people being studied, and so lose the detachment that is an essential part of the participant observer's role. Empathy therefore gives way to sympathetic bias which undermines objectivity' (2005, p. 112). My positionality as a trained electronics engineer studying other engineers and technical practitioners was, in this sense, a double-edged sword: while it provided me with a privileged position to understand, experience practical tasks first-hand and empathise with my informants, I also became highly invested in the learning part of the journey, often enticed by practical aspects and taking an interest in themes that strayed from my research questions. Being conscious about my own intellectual ambitions, my relationship with participants and the way my identity was presented was a critical aspect of navigating my experience of fieldwork. I always introduced myself as a social scientist, to discuss my intentions openly and to welcome even the most basic explanations. Still, my technical expertise and my own views were called for at different moments. During workshops and hackathons, I engaged in individual and collaborative projects, discussed technical options and even stood in front of audiences to present results. Certain formal and casual events were remarkably political, with conversations about community organisation, hacker ethics, tensions between commercial and public interests and global politics. Far from being an aloof bystander, I engaged actively in conversations and stated my points of view honestly. My presence inevitably had effects on the people and situations I encountered, which influenced the research but also spilt over other ambits outside of my academic interest. These conflicts are inherent to any ethnographic intervention, and I dealt with them by being reflexive in my writing and the interpretation of results, as opposed to espousing positivist ambitions of objectivity (Marcus, 1995).

Conclusion

In this chapter, I have laid out a reflexive account of my research journey from the early moments of exploration and negotiating access until the latest stages of analysis and writing up. I have taken stock of the process of formulating the research questions and the strategy to address them; the experience of fieldwork and gaining rapport with my informants; the practical and ethical challenges of investigating geographically dispersed sites of enquiry; and the process of making sense of the body of data. Becoming an 'ethnographer of infrastructure' (to use Leigh Star words) has been both immensely rewarding and challenging. While I have been privileged to access an idiosyncratic case throughout its early years of development and to engage with the field at a very practical and hands-on level, the multidimensional complexity of the field rendered the process of articulating a research strategy a highly difficult task.

Perhaps one of the biggest challenges of devising a research design has been to deal adequately with the distributed nature of work in the case of TTN. While previous empirical studies of complex systems offer valuable points of reference for theory and methodology, the exigencies of this project called for creative ways to deal with the issue of scale. Through a combination of online and 'offline' observation techniques, I sought to build as detailed an account as possible within the constraints of time and resources of a PhD research. While I succeeded in gathering highly detailed inputs from a range of participants and locales, this project is limited in its assessment of other geographies, particularly in the Global South. This is not only an issue of access but also one of timing considering my involvement took place at the early stages of the initiative with little or no traces of involvement in certain areas. Although I had the fortune to witness a fast-paced process of evolution throughout the period of observation, this is still, by and large, a developing case.

More data has continued to emerge after my involvement, and in that sense, there is plenty of scope for supplementary research. Deciding when to *formally* stop collecting data was in this sense a challenge in itself due to my commitment and closeness with the field over the years. Indeed, I have remained in contact with my informants and followed the developments of The Things Network after formally closing fieldwork and writing the findings of this study. Future research could not only tackle the limitations of variability I have flagged here but also aim at further engaging empirically with the long-term.

In the three chapters that follow (5 to 7), I will address the four research questions I have outlined here. I begin this analysis by tracing the evolution of the things networks and drawing the boundaries of the case study.

Chapter 5 – Geographically dispersed involvement in the internet of things: The case of The Things Network

Introduction

The Things Network grew out of an effort to open up emerging low-power networks to diverse actors by proposing to build them collaboratively drawing strongly on the principles and practices of open-source software. The initiative sparked the interest of various groups, including professional developers, academics, entrepreneurs and non-experts and has grown significantly during its early years of existence. My immersion in the field allowed me to access the internal work dynamics of TTN but also the view from the periphery as I interacted with people actively involved in the initiative. During the course of this study, the initiative has seen a fast-paced evolution, not only in terms of the technological improvements and growth but also in its core-messages and organisational structure. In this chapter, I provide a micro-level description of TTN as a step towards addressing the first research question of this thesis: 'What are the types of technical work, social organisations and technological offerings produced within TTN ecosystem?' For this task, I draw on data from multisite participant observations and interviews with contributors as well as on secondary sources, including archives and online documents.

I begin this chapter by tracing the evolution of TTN from its early inception, through its early stages of expansion until its latter phase of global scaling up in order to uncover how the project coordinators have grappled with the challenges of decentralisation and how strategies have been reworked over time. This evolution is marked by a gradual change in the discourse and the consolidation of alliances and compromises as a result of the accrued learning between different actors in the ecosystem. Subsequently, I sketch a broad picture of the TTN ecosystem and offer a provisional taxonomy of actors based on their driving motivations, their levels of commitment with the initiative and their member base. This taxonomy, albeit subject to change, reveals a highly heterogeneous universe of peripheral actors in the ecosystem.

Tracing the evolution of The Things Network

The Things Network initiative was created as a non-profit organisation within the start-up circles of Amsterdam in 2015 with the mission 'to build a decentralised open and crowdsourced IoT data network, owned and operated by its users' (Griezman, 2016). The organisation was founded by Wienke Griezman and Johan Stokking, two tech entrepreneurs who have been working together in the tech sector for a number of years. At the core of TTN is the idea of decentralisation, understood as the ability for dispersed actors to locally own, implement and operate the physical elements of the infrastructure. This notion was embodied in the organisation's original motto 'You are the network. Let's build this thing together' and registered in a 'community manifest' which fleshed out the principles of the initiative in a vocabulary of democratisation, openness, participation and membership. The brief manifest provided a set of defining principles such as neutrality and openness as well as a set of 'freedoms' (see Figure 7). In line with the principles of open source, the text of the community manifest was made publicly available on GitHub to allow for its collective writing with the help of contributors. This document served as a sort of code of conduct for an incipient ecosystem insofar as communities could either formulate their own mission statements on the basis of the manifest or, at the very least, abide by a common vocabulary.

- Anyone shall be free to set up "Things" and connect to "Things Gateways" that may or may not be their own.
- Anyone shall be free to set up "Things Gateways" and connect to "Things Access" that may or may not be their own. Their "Things Gateways" will give access to all "Things" in a net neutral manner, limited by the maximum available capacity alone.
- Anyone shall be free to set up "Things Access" and allow anonymous connections from the Internet. Their "Things Access" will give access to all "Things Gateways" in a net neutral manner, limited by the maximum available capacity alone. Furthermore their "Things Access" will allow connection of other "Things Access" servers for the distribution of data.

Figure 7: Principles in TTN community manifest (The Things Network, 2015)

Whilst the principles of the community manifest appear as a rehash of those of free and open source software, their operationalisation in the realm of infrastructure posed a series of hurdles and dilemmas owing, for one, to the significant costs involved in the deployment of physical networks. The project coordinators thus needed to adapt and rework their strategy accordingly. Over four years (from 2015 to 2019), the initiative had a rapid development marked by key milestones in its evolution (a timeline of events is shown in Appendix IV), going from a prototype network in the centre of Amsterdam to what was later described as a global network. In this period, the original proposition of TTN morphed in significant ways, going from a democratising ethos underpinned by freedom and openness to a compromise between commercial and non-commercial agendas. While TTN originated as a non-profit organisation with no business model, its operations eventually fell under the auspices of a parent organisation The Things Industries, a for-profit venture. In order to grasp this trajectory, it is worth tracing the evolution of the initiative from its inception and highlighting a few important landmarks.

I have divided the evolution of TTN into three phases (Table 3) based in the period from the inception of the initiative until the closure of data collection of this study: 1) An early adoption phase, marked by the building and testing of the first network prototype, and the early formation of communities (2015-6); 2) A phase of initial expansion, deployment of infrastructure and formation of communities, which focused on further iterations of the network software and on proposing mechanisms to grapple with the questions of sustainability (2016-7); and 3) a scaling-up phase, which is marked by the second moment of considerable deployment of local networks, the release of a major upgrade of the network architecture and the establishment of key alliances (2017-9).

Table 3: TTN Milestones 2015-2018 period

2015 to 2016	***2016 to 2017***	***2017 to 2019***
Phase 1 ***Inception and early adoption***	***Phase 2*** ***Initial Expansion***	***Phase 3*** ***Scaling up***
First use cases and pilots with LoRaWAN in Amsterdam -v0 of the architecture Kickstarter campaign for hardware manufacturing and bootstrapping Formation of first communities	New version: v1. LoRaWAN 1.1 Launched Reached 400 communities around the world, and 1100 gateways by early 2017	First conference Announcement of versions v2 and v3: open sourcing of software Reached 3572 gateways and more than 500 communities by early 2018 Delivery of the first batch of hardware to Kickstarter backers Alliances for clustering of functions and hardware manufacturing

Inception, experimentation and early adoption

In a blog post titled *The Things Network: Building a global IoT data network in 6 months*, Wienke Griezman, the strategic lead of TTN, describes the first steps in conceiving their idea. The project was concocted around an emerging low-power communication standard known as LoRaWAN[20] with the aim to leverage its open specifications and the ostensibly low costs of implementation. Coinciding with the release of the first version of the standard, Griezman and his 'tech-lead' counterpart Johan Stokking, sought to deploy and validate a LoRaWAN network prototype in the city of Amsterdam with the help of sponsors. Griezman (2016) writes:

> We needed to find at least ten businesses and citizens in Amsterdam to buy LoRaWAN gateways and host them at their premises. And we needed to write network software so all these gateways would work together as one network. Last but not least, we needed to make a story that would address a larger audience.

The very first TTN network prototype consisted of a simple architecture (Figure 8) that allowed messages to be routed from nodes to a user interface. The founders of TTN used this backend version as a prototype –the bare minimum needed—to get the buy-in necessary from sponsors to establish a city-wide deployment in Amsterdam.

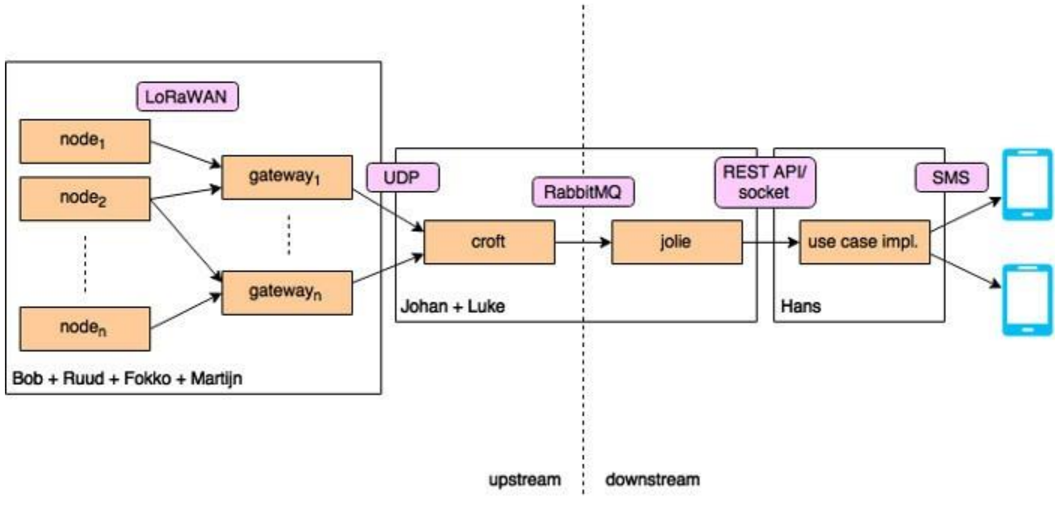

Figure 8: TTN Backend v0 (Black, 2017)

[20] The LoRaWAN specification was released in 2015 by the LoRa Alliance, a consortium founded by large tech firms and telecom operators, including Semtech, Cisco, KPN, Orange, IBM, among others (LoRa Alliance, 2015a)

Later with the support of a few corporate sponsors, an initial proof of concept consisting of a network of ten gateways was deployed in Amsterdam. Soon after, the project was officially launched, attracting the enthusiasm of early adopters who were drawn by the expectations of low-entry barriers to the realm of connected devices (Black, 2016). At the time, the LoRaWAN standard was incipient, and only a limited range of compliant equipment was available on the market. Within TTN this spurred the efforts to create appropriate education material for developers but also to engage with the design and production of 'low cost' hardware. In the same year, a crowdfunding campaign was launched to finance the manufacturing of gateways and nodes at a much lower cost compared to those available in the market[21]. This task involved coordination with various other entities and a lengthy and strenuous process of design, manufacturing, certification that extended far beyond the expected period. Yet, at the same time, the pre-purchase of equipment sparked the formation of the first batch of TTN communities around the world, predominantly in Europe.

At this stage, these communities mostly signalled an interest in the initiative or, at best, a commitment to install local networks by the time hardware was available. Communities were started by 'initiators', a role attributed by TTN coordinators to actors who would take up the task of building local LoRaWAN networks using the TTN network software but also enlist members to organise those tasks collectively. The first individuals to express an interest by signing up to a TTN account were automatically granted the category of 'initiator'. As confirmed by an initiator:

> ...So, I bought a gateway and set it up on our New York City office and hooked it to the Things Network and I immediately got an email from the Things Network saying "Ah, you're in charge" (laughs) "...and you're the initiator of the Things Network in New York". (Interview with initiator from New York, October 2018)

Pages for communities which included a list of their members, a map of installed gateways and member-curated information were a core element of the TTN website. If more than one person was involved in initiating the local community, they were designated as a 'core team' while additional people were labelled as 'members'.

[21] TTN gateways were offered on the platform Kickstarter at a pre-order price of €200, at least half the price of available off-the-shelf equipment at the time. The campaign raised nearly €300k from 934 backers (Griezman, 2015)

Similarly, a real-time global count of members was displayed on the website along with other metrics such as the number of gateways and countries and a real-time map of active gateways, showing their availability and location (Figure 9).

Figure 9: Map of gateways displayed on TTN's website (January 2019)

Educational material, as well as suggestions on how to set up a local community, were made available on the TTN website. Some of the online resources included guidelines for organising meetups, a generic slideshow presentation about LoRaWAN and TTN. Similarly, various online collaboration tools were made available to facilitate knowledge exchange within and between communities. TTN's website hosted a wiki and an online forum for members to share articles, manuals, announcements and questions. In this way, technical support was available in a peer-to-peer fashion by exploiting the collective knowledge base. These knowledge exchange practices have been a common practice in open source software communities. Core developers, as well as expert members, provided support to novices on issues with configuring endpoints, gateways and applications; bugs or errors in the console and backend; and network downtime. A central tool for support was 'Slack', where users curated content in thematic channels and discussed in real-time. Face-to-face (offline) events such as technical workshops and meetups were organised by the core team and in an ad-hoc fashion by contributors.

One of the early depictions of the network architecture (Figure 10) comprised modular elements and functions with a decentralised network topology. This architecture would allow certain components to be deployed and locally, while others remained centralised. Network architects referred to this principle as ‘separation of concerns’. At this stage, some components such as the network operation centre, the account server, the dashboard and the application server were not open source (depicted in black). This design sought to create a degree of lock-in by having contributors routing their traffic through TTN’s servers. However, members could still ‘opt-out’ from these components by developing user interfaces or registration systems on their own.

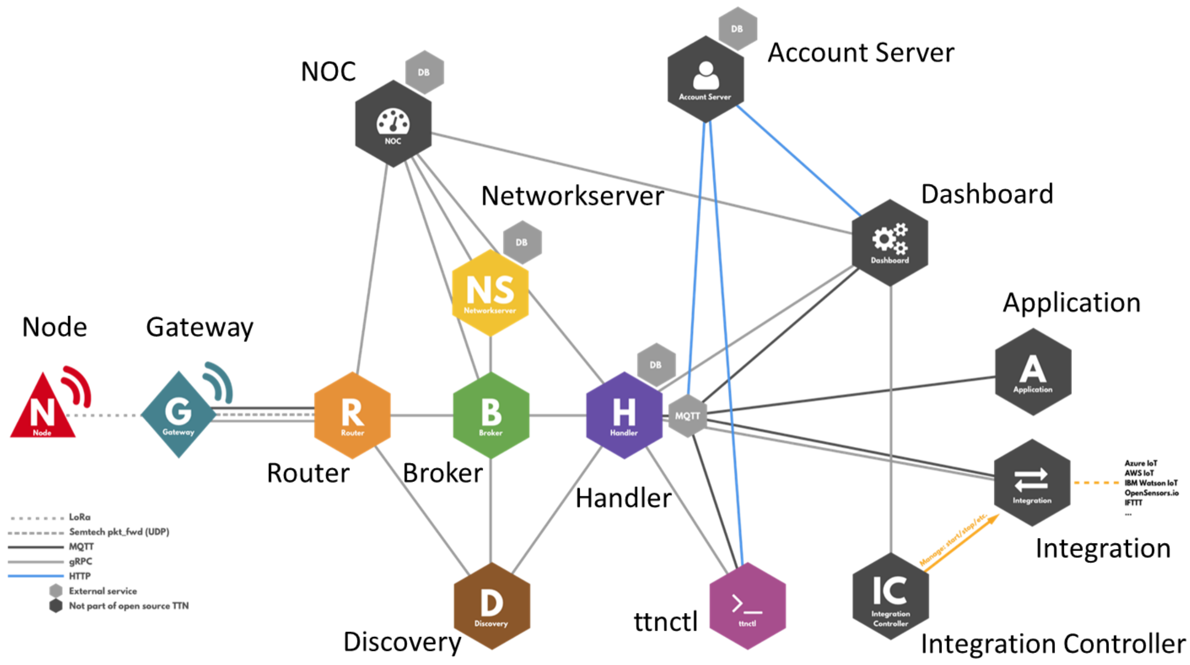

Figure 10: Diagram of TTN network architecture v2 (source: TTN website, April 2018)

This phase was marked by a period of high expectation about the manufacturing and arrival of the equipment. Although a few local actors spearheaded the deployment of networks by purchasing existing LoRaWAN equipment or assembling their own, it would stake still two years for the promised low-cost hardware to reach most early contributors.

Expanding local communities and dealing with ambivalences

The second phase (from the third quarter of 2016 until early 2017) entailed an initial expansion in terms of the number of enlisted members and an emphasis on the notion of communities as key drivers of a crowdsourced global network (an internal roadmap produced at the time is shown in Appendix V). During this phase, the network software underwent a series of frontend and backend improvements as well as the integration of third-party cloud services. In this period, support for communities was improved in different ways. Community managers within TTN implemented a classification scheme for differentiating incipient communities from more mature ones, by labelling the latter as ‘official’. Communities gained the ‘official’ status once fulfilling a set of minimum requirements, namely: two installed gateways, eight members, hosting a community meetup event and establishing a communication channel (e.g. Slack). Official communities were identified with a green ‘check’ mark on the website[22] (Figure 11). Contributors were also encouraged by community managers to share use cases, manuals, instructions and their experiences around LoRaWAN IoT networks. During this second phase, communities grew from a handful to few hundred around the world adding up to over 1000 gateways and 14000 members by April 2017[23].

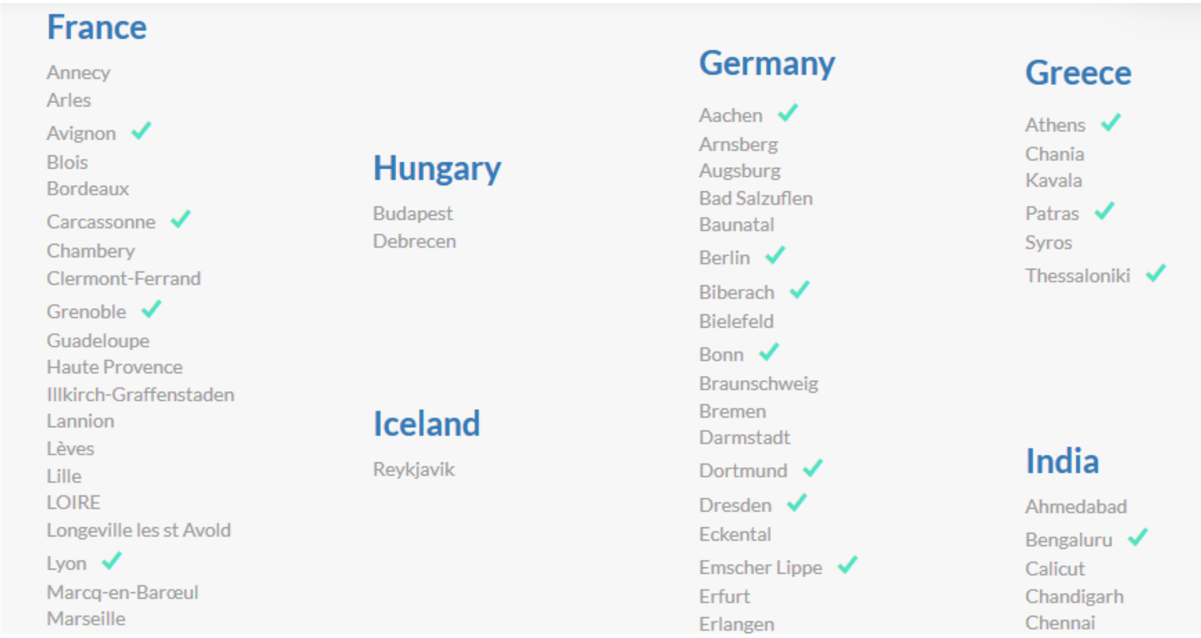

Figure 11: Labelling official communities (source: TTN website, April 2018)

A key milestone of this phase was the launch of the second version of the network software following the earlier ‘staging environment’. This iteration was known as ‘production environment’ insofar as it comprised a first stable version which allowed for the provision of services (Stokking, 2016a). This new production environment sought to consolidate a distributed network architecture and the so-called ‘separations of concerns’ whereby developers could deploy different components without having overlapping or conflicting functions. With the notion of separation of concerns, some

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[22] According data collected from the website, as of Q1 2018, only 25% of all registered communities were official.
[23] According to the official figures shared by TTN in April 2017

resources could be locally deployed while others would be still centrally operated. These modular features included, for instance, routing services (a network server), registration of devices, handling of encryption and decryption and a user interface.

Looking back at TTN's inception, the original campaign alluded to a set of descriptors (i.e. global, crowdsourced, open, free and decentralised) to convey their novel implementation model. Each of these terms not only implied values of inclusivity, democratic participation and collaboration but also a model of network deployment that counterposed established corporate approaches. The prospect of a free and open network meant not only that everyone was invited to take part in building the network but also that access to infrastructure should be provided as a public good. This raised complex questions of governance, economic sustainability, responsibilities and liabilities, and management of common resources to ensure neutrality and fair use. Although it was widely recognised that conflicting interests might exist, the problem was not explicitly addressed in the manifest. A frequently mentioned concern at TTN was that of *freeriding* or the possibility of people extracting value from the network without contributing to it. Given the finite nature of the radio frequency spectrum and the limited capacity of the network, a latent concern was that free network access could eventually lead to counterproductive competition for free resources and potential unfair scenarios. Members voiced their scepticism in forum threads and discussions and explored creative measures to mitigate the anticipated downsides.

> Forum thread: Who owns the network?
>
> Moderator: The short answer to the three questions is: the community.
>
> There is no single network: The Things Network Foundation provides source code, hardware specifications, documentation, workshop material, tools, the forum, etc, but it does not provide a network. The community creates and owns the network by buying and installing gateways, installing routers and handlers, etc.
>
> As there is no single network, there is no single point of control. Even though the The Things Network Foundation will provide a hosted router that is default in The Things Gateway, we will not enforce anybody to use this router. Everybody can set up their own networks: cities, companies, institutions, governments and communities. Those parties will be liable for the traffic and continuity of service.

> Also, gateway owners are in control of which routers they send data to: they bought the hardware and it is their internet connection. (julian, 2016)

During my on-site observation in Amsterdam, I witnessed the trial of an early prototype mechanism to enforce fair use of the network. The project was internally labelled 'value exchange' and consisted of an algorithm to collect metrics on the use and production of 'airtime' as a measure of connectivity. A record of these values, along with the number of owned gateways was displayed in the user's public profile as a way to give people a score based on their use and contribution patterns. Both measures were positively ranked, meaning users would obtain a higher rank as their use and production times increased (Figure 12). This algorithm sought to stimulate voluntary contributions to the infrastructure by making discrepancies between use and production explicit. A possible iteration to the system envisioned a decentralised virtual currency to allow people to exchange network connectivity fairly, as a proxy of peoples' 'karma' within the network. The ranking system was ultimately abandoned due to its doubtful efficacy, as exposing overuse could in fact undermine the tenets of openness, freedom and neutrality and raised concerns about hidden costs or preferential treatment of gateway owners. As discussed earlier, local efforts did not merely involve technical feats but also (hard to quantify) activities like knowledge sharing, peer support and institutional liaising.

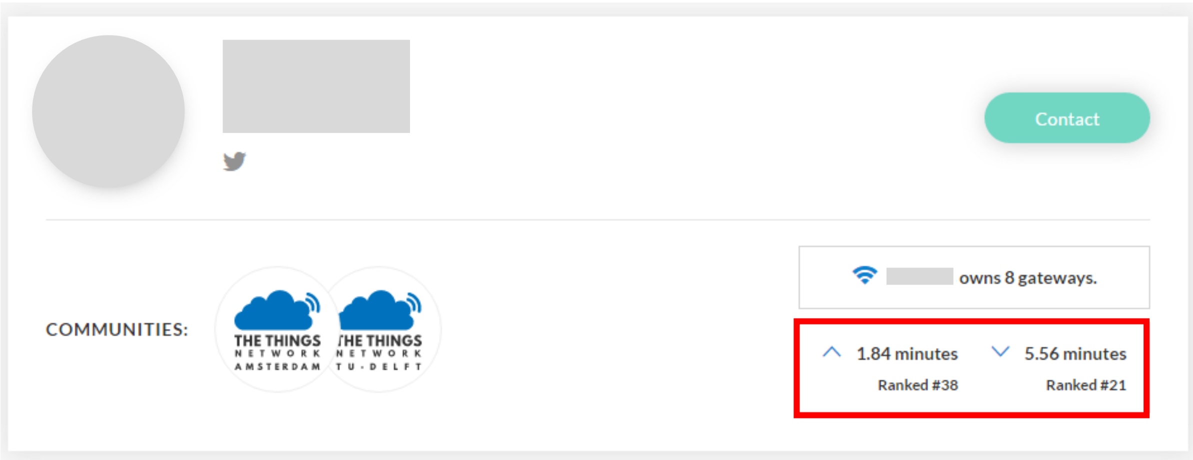

Figure 12: Value Exchange: A system for ranking resource extraction and production (source: TTN website, February 2017)

Untenable use patterns have remained in the realm of theoretical discussions, suggesting that the potential drawbacks of the *public-good* character of networks have not been a pressing concern. Instead, the focus has consistently been placed on the design of technical features to improve reliability or the production of inexpensive hardware to further reduce the cost of joining[24]. For instance, a new feature was implemented in the network software to allow overlapping private and public networks to exchange traffic between them via 'traffic peering'[25]. As explained by Stokking (2018a):

> When your private network receives a message that is to the public network you offload it to the private network and at the same time when the public network receives a message for the private network, it will be sent to that private network [...], But in order to be fair and to not have private network piggybacking on the public network, the rule is that this has to be in balance. So, if a private network contributes a thousand messages to the public network, then it gets a thousand messages back. And it also works for downlink. So that means that private network benefits from public network coverage, but they are still in full control of the infrastructure, and they contribute back to the public network. And I think that in the end, this will contribute a lot of extra coverage for the public network.

Another concern was the open source character of the network software. Although all the components of the network software were free to use, some of them were kept 'closed-source'. This raised some conflicting views among users. Some voiced their concerns about the project coordinators' claims to deliver a free and open network, as described in the original manifest, while others gave credit to TTN to maintaining the network operations free to use despite the costs. In a forum post titled 'Where is the code for console?', referring to the console not being open source, a forum user wrote: '...does this mean that TTN is moving away from its manifesto? –It states "The Things Network is an open-source, free initiative"' (heida, 2017). A forum moderator then wrote in reply:

> I think currently the following pieces can be used for free by everyone, but are closed-source:

[24] At the second annual TTN conference in January 2019 a new inexpensive indoor gateway was announced at the cost of $69 (see The Things Network, 2019b)

[25] Traffic peering is an internet concept whereby two networks share traffic between them without the intervention of a service provider and commonly for free.

- TTN Console (basic for all of us though the TTN website; more advanced with monitoring and alerting for paying customers)

- Account Server

- Network Operations Center

> Note that anything you can do with console can be done through the API or the command line interface. One can set up a fully private Handler, for end-to-end encryption without telling TTN your keys, using TTN's account server, and ttnctl to administer your devices. So, the network is open source, I feel.
>
> But even if you support TTN by hooking up gateways, or by setting up a full copy of the backend which is fully connected to TTN, then I'm afraid you still need ttnctl to administer a private Handler. (I am not sure; note that I'm just a community member, not part of TTN's core team.)
>
> Bummer, but all considered I still support TTN's decision to keep some nice-to-haves closed. Open Source projects need funding to be sustainable. If large organisations that need console on their own servers are paying for that through some commercial counterpart of the Foundation, then that benefits all. Also, keeping some pearls closed-source keeps commercial parties from just rebranding the whole thing and start separate networks. To use the frequencies and air time in the most optimal way, I feel we should get as few networks as possible.
>
> For my private projects I'll happily trust TTN with my keys. For work related things, I don't mind getting my employer to invest in a private installation with a working Console (arjanvanb, 2017).

This explanation was later confirmed by TTN's tech lead:

> Fully supporting @arjanvanb's answer. All components that are needed to run The Things Network are open source, but there are also complementary components that are closed source (Stokking, 2017).

The source code was kept closed in elements that were thought to be complementary and not critical to the operation of the network, which in turn, allowed TTN to keep a unified register of users which provided a mechanism to underpin the idea of an interconnected network as opposed to isolated ones. Still, private deployments could, at least in theory, be fully detached from the central closed source elements insofar as customised instances of these elements would be put in place. At this stage, much of the discussion and debate revolved around the question of how the free and open infrastructure proposal of TTN was to be made sustainable. Although the project coordinators had already been taking some steps towards establishing a line of business[26], this was unofficially announced on a forum thread:

> The Things Industries is a legal entity separate from The Things Network Foundation, that develops the components and donates open source components to the Foundation. It also manages the infrastructure for the public community network, but I can imagine that the Foundation will become more autonomous in the future, possibly in an association model with members. Wienke and I are currently investigating different governance models to make the Foundation more independent and continuous (Stokking, 2016b)

In parallel with the search for a business model, additional steps were taken to incorporate renowned third-party cloud services to the TTN network software. Commercially available cloud services would allow application developers to access a wealth of advanced data-processing tools already available in the market such as data analytics, storage and visualisation tools. At this stage, the roadmap primarily envisaged integration with IoT platforms such as Amazon Web Services, IoT Azure, IBM Watson, along with half a dozen other names. Ultimately, TTN aimed to offer compatibility with as many major third-party options as possible, and thus the network architecture was described as' technology-agnostic' to emphasise its ability to work seamlessly with different complementary systems. The work of integrating these services entailed a process of translation and linking up of TTN software through the use of public APIs.

Finally, the delivery of the promised low-cost LoRaWAN equipment was a crucial milestone at this stage. Indeed, many of the first TTN networks around the world were deployed once this hardware was available.[27] The delivery of devices was severely

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[26] According to my fieldnotes taken on April 2017, during my stay in Amsterdam The Things Industries was created as a parent organisation of The Things Network Foundation with the aim to ensure the financial stability of the initiative

[27] According to data collected from The Things Network website the number of active gateways was of 3661, compared to 2000 observed in December 2017. This increase marked the delivery of the first batch of hardware to the supporters of the Kickstarter campaign in January 2018, which meant that at least 1500 new gateways were installed as part of the global network, either to improve existing coverage or to start new network deployments

delayed due to numerous technical, logistical and legal challenges faced by an organisation that was new to the complexities of hardware manufacturing. Backers widely expressed their concern and discontent, some of which even accusing the organisation of selling *vapourware*. This was a period of high uncertainty and frustration during which TTN leaders gave out continuous clarifying statements along with assurances that the products were going to be eventually delivered.

The manufacturing of hardware, albeit foreign to the field of expertise of TTN's core team, was seen a necessary step to persuade people to join the global project by helping to lower the cost barriers. Indeed, TTN's core team did not include any hardware developers, so to fulfil this task, they liaised with external product designers, suppliers and manufacturers in China. Lastly, prior to fulfilling their hardware delivery, different processes of compliance and certification had to be thoroughly carried out. This milestone not only helped to underpin the narrative of a growing installed base of TTN but also gave some credence to the initiative after a long-overdue commitment to its early supporters.

Devising a hybrid model and establishing key alliances

In February 2018, the first TTN conference was held in Amsterdam with a lively programme of workshops and keynotes speakers the LoRaWAN ecosystem at large (The Things Network, 2018). The conference was a meeting point for the different actors, including developers, entrepreneurs, community initiators, academics and diverse technology vendors. At the conference, the TTN leaders officially launched the latest major version of the network software which had been in development for almost a year. This event marked a turn to a full-fledged modularisation of the network architecture and a compromise between non-commercial and commercial agendas. Network architects at TTN underpinned the benefits of modularity by the need to improve the quality of network deployments by allowing elements to be coupled and decoupled more easily and physically closer to people's facilities. In this way, network components could be installed and dimensioned as needed while improving reliability, latency and security. Johan Stokking (2018b) described the new architectural design of the network as a combination of discrete open source elements: 'All of these components will be open source and MIT licenced, that's also a big change from V2' (Stokking, 2018b). In this new iteration, elements were grouped into standalone functional instances, each of them with the ability to be either deployed 'on-premise' or 'hosted' in the cloud (Figure 13).

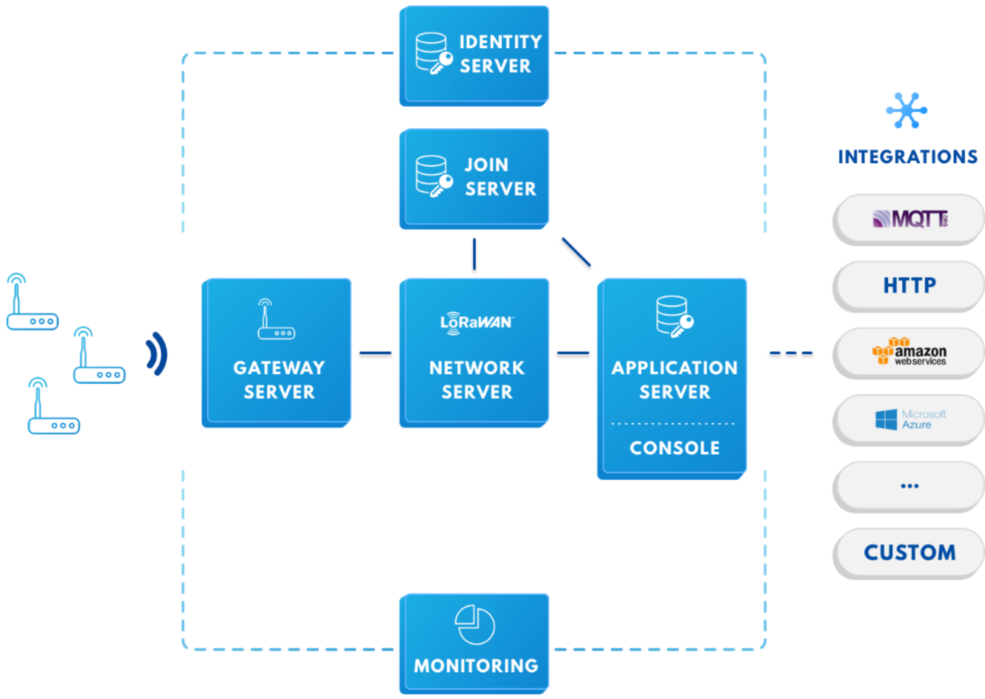

Figure 13: Diagram of TTN network architecture V3 (source: TTN website, October 2017)

The new version of the network software had significant improvements to the architecture characterised by the compartmentalisation of functions and the open-sourcing of all components. While previously specific proprietary components of the architecture were seen as a mechanism to support a business model and a unified global network, the full open-sourcing of code signalled a privileging of decentralisation over conflicting monetising strategies. This is not to say that the need for a business model was side-lined; but indeed, quite the opposite. The popularity of the standard, the accrued knowledge and the proven efficacy of the network were seen as a means to offer value-added commercial services. In other words, a public and free-to-use community network would coexist with a portfolio of enterprise-oriented services that leveraged positive network externalities (a point I shall return to in the next chapter). This move was touted as a means to reduce costs and avoid lock-in but also as a move towards granting members more control over the infrastructure. In a letter titled 'No permission required' sent out to members in May 2017, TTN leaders had already anticipated the next iteration of the architecture while flagging the need for a balance between openness and sustainability:

> Our new architecture allows you to run the routing services *yourself*. By doing so, *you* are in control of the quality of service and level of security. Above all, you can still contribute to and leverage the global community network, by opting in for network collaboration from the network server. All of this completely secure and end-to-end encrypted, leading to a higher level of decentralisation and distribution. This way more parties besides The Things Network organisation will support the network's backend, which will result in a more sustainable model (Giezeman and Stokking, 2017, emphasis in original)

The letter clarified some of the doubts about TTN that have been looming since the outset:

> **Can I get a Service Level Agreement on The Things Network?**
> *Yes, you can now build QoS networks by taking control over the hosting of the backend.*
>
> **Can I run The Things Network privately on my own servers?**
> *Yes, our open source software is able to run on your own server.*
>
> **Can I setup end-to-end-encryption for my application?**
> *Yes, you can now add software to your application so you can fully leverage the end-to-end security of LoRaWAN.*
>
> **Can I run my business on The Things Network?**
> *Yes, the more value we create on the network the better.*
>
> **Can I use enterprise class features?**
> *Yes, including features like multicast, OTA firmware updates, monitoring & alerting etc.*
>
> **How do you guys make money?**
> *The Things Network is now sponsored by our business* The Things Industries *which provides an enterprise grade network server, hosting and support. We invite you to build your business on top of The Things Network as we are building a broader ecosystem that can make the network more sustainable.* (Griezman and Stokking, 2017)

The affordances of the new network architecture meant that certain components could be operated in a more distributed fashion, with some key resources shared at the local level. Thus, in tandem with the release of the new network architecture, a call was made for strategic allies to run key network components locally and in that way act as regional representatives of TTN. This formal delegation of the responsibilities signalled a need to ensure the operation of a global network. The intention in this sense was to scale the global network through a so-called ‘clustering’ or outsourcing of network functions to veritable partners. The idea of regional clusters was not new, as some of the more stable communities in the TTN ecosystem (e.g. Zurich, New York and Sydney) had up till now operated as de-facto brokers of network components in order to reduce latency, improve uptime rates and balance the load in the system. In the second edition of TTN conference held in early 2019, more strategic alliances were announced with manufacturers, operators and vendors, and a stronger emphasis was placed on the ‘industrial-grade’ use of the network[28]. In a subsequent interview, Wienke Griezman acknowledged that public connectivity was a ‘scarce resource’ and hence there was a need for market mechanisms as a means for sustainability and commercial viability:

> We see that all these resources are a commodity. That the business case of sharing network is in that you leverage the network always more than you contribute. That is because the model is not a zero-sum game. As more gateways generate more efficient routes in the network and opening up your gateway gives you access to more efficient routes. There is no need for “value exchange” (Griezman, 2019).

The hybrid model of TTN signified a pragmatic compromise: the coexistence of a public infrastructure operated in a ‘best effort’ fashion and a portfolio of enterprise-level network services. While the former is commonly touted as a provisional learning tool and testbed preceding *live* implementations, it has been maintained as a stable network owing to the collective effort of communities and the support of strategic partners. The public network at the same time underpins the portfolio of professional services offered by the TTN profit-oriented counterpart under service level agreements (SLAs)[29].

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[28] As of May 2020, the updated motto on the website read: ‘Supporting 108322 developers in building industrial grade LoRaWAN solutions’

[29] According to TTN 2018 metrics, the availability of the public network servers was 99.986% -the equivalent to an average downtime of 6 minutes per month. In contrast, a slightly lower guaranteed SLA (Service Level Agreement) of 99.9% is offered by TTN for-profit parent company (The Things Industries) for a price (Stokking, 2018c)

With the hybrid model, TTN offered both the possibility for members to implement public or private deployments while embodying a commercial organisation offering complementary services. In this way, the attempt was to accommodate non-commercial and commercial interests under a single vision without resourcing to lock-in and compelling members to opt-in for paid services. This move was, however, not an innocuous one as I discuss in the next chapter.

Mapping the TTN ecosystem

TTN has strongly emphasised its model of cost-efficient and collaborative construction of IoT networks and applications. Such a proposition has attracted a highly diverse range of people including hardware and software developers, entrepreneurs, academics and non-experts. These actors have been variously referred to as contributors, members or initiators insofar as they partake in the initiative in different ways according to their domain of expertise, their motivations and their specific needs. Many of these actors are not new to the industry and have brought with them vital stocks of technical and organisational knowledge. Indeed, some of the groups I interacted with during fieldwork were well acquainted with the world of telecommunications, the emerging trends of IoT technologies and hardware manufacturing. Others have for years been actively involved with the construction of wireless community networks or with hackerspaces, and yet others have also contributed to policy and academic discourse on the matter. The emergence of TTN constituted an interesting site of action for some of these groups, and at the very least, provided a space for deliberation and critique for others.

In the remainder of this chapter, I sketch a map of the actors directly involved with TTN either through carrying out work on building infrastructures, applications and solutions, or generating knowledge and debate around the initiative. For the purposes of this mapping exercise, I define the TTN ecosystem as comprised of two broad groups: a coordinating (core) group and the universe of geographically dispersed (peripheral) actors.

The Core Team

My early encounters with TTN were through phone conversations with the founders and later with the two community managers in the months preceding the study. I then met the rest of the team during my immersion in the TTN headquarters in Amsterdam in February 2017. Their office was located in the underground floor of a business accelerator firm located in the centre of Amsterdam. Within this environment, TTN stood out from the other organisations cohabiting the space, most of them start-ups, as the only non-for-profit. At the time, the internal team (known as the 'core team') consisted of 15 people, 4 of whom worked remotely. The two founders worked daily from the office and split their functions into technical and strategic leadership. The rest of the team included six software developers, a network architect, a business lead, two community managers, a designer, an external hardware developer and an intern student. Within the period of observation (from 2015 to 2019) these roles evolved alongside the initiative and the staff grew slightly to a team of around 20 people. Most of the staff were recruited as full-time or under traineeships and internships, while a few of external partners and consultants worked in a part-time basis.

The activities of the core team were primarily focused on the design, development and operation of the network software. This task involved a combination of backend and frontend development and architecting of the network, but also the management of the open-sourcing of code; the regular monitoring of the performance of the network; and the continuous support to contributors engaged with deploying local networks. The development team worked under an agile methodology comprising a fast and incremental process of designing, building, testing and delivery. All the members of the core-team met daily in 15-minute-long stand-up meetings, where briefings about the current state of the work were shared. The first outcomes produced by the team of developers were the network architecture and a functional piece of software that fulfilled the task of getting messages from the gateways to the network servers. Further iterations to the network backend such as end-to-end encryption, bidirectional communication and integration with third-party services were built on top of previous iterations.

Building the network backend required a strong understanding of the LoRaWAN specification. Getting acquainted with the inner workings of the standard entailed not only an in-depth study of the available documentation but also a direct channel of communication with the standard developers, which helped to resolve emerging issues. The network software kept a high pace of development and incorporated new functionalities soon after the release of new versions of the LoRaWAN specification.

The team of developers employed various open-source and proprietary development tools including programming languages, virtualisation and containerisation software, on-premises and cloud-based servers, and various third-party services for storage, processing and collaboration.

Another critical role within the core team was that of community managers. Community managers were the first point of contact for external contributors and generated communication material and strategies to shape the notion of local communities as the main drivers of a distributed global network. One of the central activities of community managers was to pitch the initiative at events such as meetups, technical workshops and industry meetings and to encourage initiators to hold meetups and promote the initiative locally. Indeed, I carried out a great deal of my observation through working closely with the two community managers who also helped me to connect with many of my external informants. Community managers were routinely in contact with initiators which gave them a good acumen of the universe of members and the state of affairs at different locations. The strategies around scaling up and business development were closely worked out with community managers. Their work directly informed decision-making and the drafting of medium- and long-term planning of the initiative, which was embodied in quarterly roadmaps with the involvement of all the members of the core team.

Although the initiative undertook the task of delivering low-cost hardware, the core team did not directly engage with hardware development and relied on the expertise and knowledge of external partners to carry out these tasks. The development of the first batch of TTN hardware was therefore outsourced to a product development firm with expertise in product design and mass manufacturing, while further hardware offerings were produced in agreement with established hardware vendors in the industry. Similarly, the core team did not focus, at least at this stage, on application development as an internal competence. Although services and solutions have become central in the agenda over the years, only a handful of demonstrative use cases were developed in-house at the time. Most of the applications that were showcased in presentations and events were carried out by external actors and emerging firms participating in the domains of application of low-power networks. Ultimately, the development of applications was an activity relegated to the sphere of action of what I call ‘peripheral actors’.

Peripheral actors

The TTN ecosystem was conceived as an array of geographically dispersed communities formed by volunteering contributors. Communities have been at the core of TTN's strategy to crowdsource the deployment of networks and decentralise key components and competencies. In the course of this study, around 500 communities spawned in cities around the world with members coming from a diverse and broad range of backgrounds. While many of TTN contributors came from a demographic of people with expertise on related technical areas such as hardware development, programming and network engineering, others belonged to non-technical entrepreneurial and business development spheres. In this mapping exercise of the TTN ecosystem, 'peripheral actors' encompass the universe of individuals and communities taking up the task of deploying, operating and using local networks.

In general, rolling out local LoRaWAN networks involved a range of activities including the commissioning and maintenance of physical elements (primarily gateways) and the monitoring and troubleshooting of the network. Community members also engaged in various educational and evangelising activities which were considered central for furthering their agendas. Learning at the local level was supported through different mechanisms of knowledge sharing, such as hands-on workshops or peer-to-peer support. These activities were carried out on a part-time basis by interested professionals, as explorations of alternative lines of business in technology companies, or as full-time projects by researchers, entrepreneurs, retirees and other interested audiences.

The existence of a community was however not always an indication that members were running or even using an installed network insofar as individuals and communities could register in the TTN systems without the need to own or operate a gateway. Indeed, for the most part, the formation of communities constituted an initial expression of interest in the initiative, while the actual investment in infrastructure, if at all, ensued slowly over time. A challenge for these communities was to attract and keep a base of members. As voiced by an initiator: 'If currently we have 20 or 21 (gateways) that's good, but we prefer to have people coming to our meetings and bringing their knowledge to the community, more than having more gateways' (Interview with a community initiator from Madrid, March 2019).

One of the key metrics used by TTN to account for the efforts of peripheral actors has been the number of active gateways registered in the TTN network. The significance of these numbers, however, varies from one location to another. A high density of gateways in a city could, for instance, be an indication of an operational network, a cohesive community or a private project. A good example is the case of Zurich where community members organised to strategically deploy gateways to provide a highly dense city-wide LoRaWAN coverage. However, a higher number of gateways does not necessarily translate into operational networks. Indeed, the lack of coordination between individual members could lead to duplication of effort and inefficient placement of gateways. Similarly, contributors could install networks independently of communities, either for learning and experimenting or for private projects without the need to officially affiliating to an existing community in their location.

> ...right now what we have is personal initiatives, each of us acquire*s* gateways, and we install and operate them. We indeed carry out activities for those who are not initiated in this world so that they can get started and we help them to start their gateways. But they remain their property, and they install them, maintain them and do with them what they want ... This type of deployment is very inefficient because gateways are normally installed in the residences of these people or their workplaces, but it then happens that we have coverage of some areas and none in others. So what we are trying to implement through the community here in Madrid, is a system by which the community acquires the gateways and they are installed in very favourable locations, at very high points. And we are trying to organise this through internet providers who give wi-fi connection to remote neighbouring communities or to those that do not have good fib*re* optic coverage. On the other hand, we are also trying to do it through the community of radio amateurs who already have really unique locations in Madrid (Interview with a community initiator, March 2019)

Along with the construction of networks, the development of IoT use cases and applications was also a central activity performed by peripheral actors. Applications are contingent on the specific needs and circumstances at each location. In turn, the requirements of applications have direct implications on how networks are dimensioned and scaled up. These development practices involved arduous learning efforts which are facilitated variously through educational activities, technical workshops and testbeds.

Drawing on existing data about contributors leads from the community managers, field trips and interviews with community initiators, I identified four different assemblages within the ecosystem. The criteria used for this classification include the different forms of commitment to the initiative, their member base, their forms of organisation and their motivations (see Table 3). This mapping exercise, however, is contingent on the fact that the universe of peripheral actors is not static with local communities and initiatives continuously spawning, evolving and dissolving. Therefore, this taxonomy is not intended to be fixed nor exhaustive but instead offers a broad picture of the diversity of members and motivations within the ecosystem. Moreover, these groups are not defined in a hierarchical way or by sharp boundaries between them insofar as their status is subject to change over time and members could be affiliated to more than one type of assemblage.

Individuals and incipient groups

At the time of my enquiry, many of the locations shown in the global map of communities were not full-fledged communities but rather dispersed individuals and incipient groups of people in the early stages of getting acquainted with the technology and with no clearly defined goals. In the absence of an existing cohesive community, a small number of individuals engaged with TTN for personal motivations and generally out of sheer curiosity for the promise of TTN. A common site of encounter in various cities has been existing groups of techno enthusiasts and hackerspaces who would have a space for discussing and taking part in experimenting with LoRaWAN. Although these groups did not necessarily seek further endeavours as a community due to their small size, some of them pursued private ventures and the development of concrete applications.

> …so I registered, and I obviously didn’t read carefully because I happened to become the community leader of Basel because I was the first one in Basel to sign up for it. But I said, well why not? I mean it’s an interesting concept and so I started doing meetups and it was really amazing that they already in the first meetup ten people showed up. So, I mean, of course, it’s an interesting topic its IoT, sensor stuff, a lot of things that are going on with the topic of smart city or industry 4.0. So all these buzzwords, of course, they attract people. We’ve had a lot of people come and go but that’s basically how everything started in Basel. (Interview with a contributor, October 2018)

Formalised Communities

Particularly in large cities, more cohesive assemblages have moved on to formalise their activities through various mechanisms and organisational structures. Some communities have established non-profit organisations, foundations, associations or cooperatives with the intention to propose alternative modes of infrastructure ownership and management. The main difference with the previous category, in this case, is the existence of shared goals, a higher level of commitment of time and resources, and a focus on democratic decision-making. Some of the groups I interacted with grew out of specific projects or initiatives with a clear goal in mind, for example, the implementation of an environmental monitoring network. Although their members are not necessarily devoted solely to the operation of the organisation, there is a degree of professionalisation involved with their enrolment. Formalised communities have established different mechanisms to deal with issues of funding, legality and institutional coordination, and a consideration of different (commercial and non-commercial) paths to sustainability.

> Above all, we were concerned at that time about what was the legal responsibility of a gateway operator? What are the legal obligations that a gateway operator may have? And whether we could manage it with a legal entity that could decouple personal responsibility? We started talking about it, the conversations went on for a long time because of the community dynamics. In October we finally managed to get the forces together and discussed the statutes which is the only thing needed in Switzerland to formalise a legal entity. In October we finally got together, we were 23 founding members, it is an association that is like a non-profit organisation (Interview with a community initiator, March 2017)

Private ventures

Private ventures are perhaps the most common incentive in the ecosystem to deploy and scale local networks. In this effort, the provision of networks is guided by a business case or a specific commercial opportunity. Private efforts seek to establish a means of selling advance network services, applications or full solutions. Institutional links, as well as goals and potential sources of funding, are generally identified prior to the construction of private local networks. Central to the work of these actors is the need for a business model and a sustainable stream of funds. Over time, the perspective of core-developers' has shifted from the creation of communities towards a more entrepreneurial involvement of contributors where the focus is on the development of services and solutions. Some private ventures in the ecosystem such as Meshed in Australia or CyberEye in India focus on the integration of services and the delivery of 'turnkey' IoT solutions.

> We are providing a complete data platform behind that can receive the data. We do some monitoring, some prediction of the data, trigger some alerts and process all this information to do some prediction (Interview with a business developer, June 2017)

Research and innovation initiatives

Research projects and innovation initiatives have turned to TTN software as a cost-effective way to establish testbeds to conduct experiments and promote innovation. This type of assemblage is contingent upon the sources of funding and the institutional dynamics where these initiatives are embedded. The establishment of testbeds provide a structured way to involve proxy users in technology development and lower the costs of testing and validation. Innovation programmes such as the UK Digital Catapult, for instance, have established an alliance with TTN local communities to promote the development of IoT products and services: 'This collaboration brings together two well-established initiatives in the UK, creating Britain's largest free-to-use LoRaWAN network and innovation community' (Digital Catapult, 2018). Another example is the deployment of an experimental IoT research testbed at the University of Edinburgh which was provisioned as an available service for students and researchers to experiment with IoT devices and applications (IOTRIS, 2017).

Table 4: A taxonomy of peripheral actors

	Members	*Sources of funding*	*Examples*	*Goals*
Individuals and incipient groups	Tech enthusiasts Hobbyists, Professionals	Own funds	Clubs, meetups, Hackerspaces	Experimentation Learning, Own use
Formalised communities	Tech enthusiasts, Engineers, Developers, lawyers, activists	Own funds, donations, membership fees	Foundations, Associations, Cooperatives	Experimentation Provide coverage in the locality, Addressing community needs

				(air pollution monitoring)
Private ventures	Engineers, developers, IT managers, entrepreneurs	Private investment Revenue from products and services	Business units, Start-ups	Application development, Deliver IoT services and solutions
Research and Innovation initiatives	Engineers, researchers	Research and innovation grants	Innovation testbeds, Research projects	Testing and experimentation Research Provision of IoT services

Conclusion

In this chapter, I have outlined the temporal and social dimensions of the case of The Things Network. First, I have traced the trajectory of the initiative from its early phase of experimentation to its stage of global scaling up. Over the course of four years, TTN underwent a rapid process of validation, experimentation, and learning while grappling with the challenges surrounding the construction of a global IoT network. The unusual proposal to decentralise network components in a modular fashion has attracted thousands of users and triggered the formation of hundreds of communities around the world. However, this trajectory is characterised not merely by the overall increase of the installed base and the number of new communities[30]. The initiative also underwent an incremental reworking of the original ambitions settled at the outset in the community manifest. While the notion of openness has remained at the core of the initiative, there has been a marked turn towards the creation of IoT services and solutions. The initiative has proposed to lower the barriers to enter the field of IoT and has pursued this mission from various flanks including infrastructure, hardware and software. While TTN has so far succeeded in achieving an ostensibly implausible goal, the ensuing manifestation of the project, far from following a linear path from conception to concretion, has been the result of a highly unpredictable and collective effort.

[30] At the time of the closure of the observation period of this study in August 2019, there were over 8000 active gateways while the number of registered members surpassed the 80,000 (The Things Network, 2019c)

In the second part of this chapter, I have delineated a map of the terrain by looking at the practices and forms of organisation of the different groups involved in the initiative. The TTN ecosystem is comprised by a core coordinating group and by a universe of geographically disperse contributors (or peripheral actors). The latter group, in turn, subsumes a diversity of 'versions' of the way local networks shall be reproduced at the local level. Based on my research fieldnotes, the personal histories of community initiators and the available data about TTN contributors, I have identified four broad types of assemblages: incipient groups, formalised communities, private ventures and research/innovation initiatives. The view from peripheral actors evidences the heterogeneity of the ecosystem and the situated and changing nature of work. The motivations and inputs of a range of disparate actors have played a critical part in shaping the initiative. From the point of view of the project coordinators, steering the trajectory of the initiative thus seems all but a straightforward task of management. I discuss this issue at length in chapter 6.

As discussed at the start of this chapter, the technical features of low-power networks allow for the deployment of sensors which can be used in a diversity of applications, ranging from environmental monitoring networks to sophisticated 'smart' solutions. In the case of TTN, while experimental networks are built for purposes of learning, these networks are scaled up mainly on the basis of specific projects. Commercial and non-commercial projects are carried out by peripheral actors through different forms of organising work and securing funds. The scaling up of networks is thus contingent on how the opportunities to innovate are harnessed by the local actors. In chapter 7, I deal with innovation as a crosscutting theme surrounding the construction of data infrastructures.

Chapter 6 – Distributed Infrastructuring in the Internet of Things

Introduction

Telecommunications networks have been traditionally built in a top-down fashion relying on access to big capital, vertical integration of processes, centralised management and national and regional institutional coordination. This strategy is also largely applied in the realm of IoT, not only for the deployment of backbone networks such as LTE and 5G, but also for the rollout of low-power networks (LPWAN) such as NB-IoT and SigFox and LoRaWAN. The decentralised proposition of TTN, however, is an unusual one and is far removed from the conventional *modus operandi* of large network operators in the landscape of IoT. On the one hand, it entails a delegation of the rollout of dispersed implementations to local actors in order to spread out the costs of deployment and on the other hand, it pledges to be of global scale through the use of a common network architecture as a means for interoperability. Although some of the strategies used by TTN advocates seem to be strongly informed by prior efforts of collaborative technology production such as open-source and wireless community networks, TTN has encountered a whole new range of challenges and experienced a steep learning curve throughout the years.

In this chapter, I address the question of 'what are the factors influencing the decisions to initiate and operate local TTN networks and what are the mechanisms for aligning and coordinating work between geographically dispersed actors?' To do this, I examine the diversity of interests within the TTN ecosystem as well as those of the initiative coordinators. My aim is thus is to scrutinise the ambivalences and dilemmas encountered by the different actors within TTN in the process of deploying low-power networks in a distributed fashion. As a direct result of wrestling with this question, I also deal with my third research question which concerns the possibilities and opportunities for TTN coordinators to steer the initiative and achieve their objectives. I will then discuss how different strategies have been tried out by core developers and the efforts to resolve the encountered ambivalences and dilemmas.

In order to unpack the challenges of building IoT networks, I focus on the different work practices of the actors inhabiting the TTN ecosystem. By work practices, I will refer to those activities surrounding the construction of data networks and applications. These include design, prototyping, development, network architecture, implementation, field testing, monitoring and troubleshooting. I aim in this way to shed light on the difficulties behind aligning different interests within a global-scale network and explore how (and whether) disparate motivations find a compromise regardless of their divergences. For the analysis, I take an infrastructural perspective in order to move away from the descriptions of IoT as simply a cluster of technologies to a multidimensional view that takes stock of the sociotechnical, geographical and temporal aspects (Edwards *et al.*, 2007). As a discussed in Chapter 3, this analytical method may not only inform decision-making, but it foregrounds the political, ethical and social aspects of infrastructures (Edwards *et al.*, 2007; Bowker *et al.*, 2010; Star and Bowker, 2010).

As a starting point, I describe the internet of things (and more specifically low-power networks) as 'data infrastructure' by looking at some of its infrastructural characteristics. Based on this definition, I then look into how TTN coordinators have grappled with growth and lock-in effects in the pursuit of their decentralised model. Different motivations, preferences and forms of organisation are subsumed in the TTN ecosystem. This calls for an assessment of the strategies and mechanisms used by central and peripheral actors to coordinate their work. The concept of distributed infrastructuring is proposed as an attempt to capture how the piecemeal work of geographically dispersed actors is brought to bear on the purview of a global network.

The internet of things as 'data infrastructure'

> With the rise of decentralized technologies used across wide geographical distance, both the need for common standards and the need for situated, tailorable and flexible technologies grow stronger. (Star and Ruhleder, 1996, p. 112)

In their ethnography of the Worm Community Network (WCN), a decentralised information system for scientists conceived in the early days of the internet, Star and Ruhleder (1996) described the series of challenges that arose from developing a common system for a wide universe of users. This case is an illustration of the paradoxical nature of infrastructure-like systems which need to be flexible enough to cater for the diverse user requirements and at the same time sufficiently rigid and standardised to be able to operate stably over time. Reflecting on the failures of the

WCN, the authors highlight the mismatches between detached pre-structured systems and existing work practices and argue for the need to problematise the relations between people and technology. This paradox has been a recurring issue in empirical studies of information infrastructures and has been variously formulated in terms of tensions or dilemmas (Hanseth, Monteiro and Hatling, 1996; Edwards *et al.*, 2007; Ribes and Finholt, 2007). As I will discuss in this chapter, the paradox between flexibility and stability is very much a latent issue and a source of contention in the construction of IoT networks. Yet, in the wake of data-oriented technologies such as low-power networks, it seems relevant to revisit the concept of 'information infrastructure'.

The purpose of the WCN, in much the same way as that of other complex systems which have been broadly characterised in the literature as information infrastructure, revolves around the need for delivering information resources to a community of users (in this case scientists) (Hanseth, Monteiro and Hatling, 1996; Hanseth and Lyytinen, 2003; Bowker *et al.*, 2010). However, in the context of low-power networks, the focus seems to be placed almost exclusively in the collection and transport of data. The case of sensor networks is perhaps the best illustration of systems oriented to the collection of vast amounts of very fine-grained data through the use of sensors. While this data may indeed be processed and rendered into coherent reports and visualisations for their readily consumption, the value of IoT networks predominantly lies in the aggregation of multiple sources of data and its potentiality to enable complex functions of automation and prediction.

Practitioners use the term 'data networks' to broadly refer to sensor networks and low-power networks which highlights their prime focus on data collection. In line with this rationale, I shall use the label 'data infrastructures' as a means to emphasise the heightened focus on data of low-power networks. This characterisation however is not intended as a new freestanding category but constitutes if only a specific form of information infrastructure.

With these considerations in mind, the internet of things can be described in terms of a set of infrastructural characteristics (Star and Ruhleder, 1996; Edwards *et al.*, 2007; Ribes and Finholt, 2007):

- *Embeddedness/built on an installed base*: The IoT is built on top of the existing internet. It is not only technically an overlay structure that is embedded in an installed base, but also in the histories of developers themselves and in many of the same social structures, institutions and conventions of the internet. Low-power networks are, for instance, reliant on backbone networks for transportation and point of entry to the internet.
- *Scope and scale:* The scope of the IoT is not bounded to a single domain but spans multiple social, spatial and temporal dimensions. Low-power networks, in particular, are intended to cover long distances, scale up and sprawl across geographical domains. But more crucially, data networks are intended to remain stable over time and therefore, long-term planning, maintenance and troubleshooting are critical considerations.
- *Embodiment of standards:* The internet of things is largely shaped by how standards are implemented. Standardisation is critical for interoperability and stability in the internet of things. Moreover, in the landscape of the IoT, there is no single unified system, but an agglomeration of multiple sub-infrastructures based on different standards and modes of connectivity. The Things Network initiative, for one, co-evolves with the LoRaWAN standard: the topology of networks and their specific functions are dictated by the affordances of the LoRa protocol and the LoRaWAN specification.
- *Learned as part of membership*: Building the internet of things requires a great deal of learning and knowledge exchange. The more proximity there is with its inner workings the more knowledge and awareness about its components there is. Within TTN, this has been a crucial factor insofar as organising decentralised networks has strongly relied on facilitating mechanisms for learning and training.
- *Relative invisibility/Taken-for-grantedness:* invisibility is perhaps one of the more anticipated features of the internet of things notably heralded in predictions such as ubiquitous computing or the moment when computers would 'become part of the environment' (Weiser, 1999). Yet, the vision of sensors blending with the environment is still largely an ideal as we are constantly confronted with the proliferation of smart objects and the existence of wireless networks and the internet. Invisibility in this sense is rather an *aspirational* feature insofar as the IoT is nowhere near invisible to practitioners

and a whole range of concerned actors. Although data-oriented business models and the idea of surveillance capitalism are increasingly taking more relevance, it may still be too early to assert that the IoT and data-oriented infrastructures have become normalised and taken-for-granted.

These dimensions, defined in terms of sociotechnical relations, offer a more nuanced view of the internet of things as they foreground how large-scale systems are imagined and perceived by their different users; the existence of social conventions and layers of existing structures; and the linking up of hard-to-grasp global dimensions with the concrete work carried out at the local level. Building on an infrastructural view of the IoT, in the rest of this chapter I will focus on how the construction of a global data network has been conceived and pursued within the TTN ecosystem and how risks and benefits have been weighed in strategic decisions towards scaling up.

Grappling with growth in a contested landscape

The tension between the need for stability and flexibility renders the construction of infrastructural systems a highly complex endeavour. This issue is particularly salient in the internet of things given its fragmentation, the diversity of domains or verticals, and the variability in the types of network implementations. Moreover, this study unfolds in the midst of fierce competition between LPWAN standards with emerging business models and technological propositions and with no clear winners in the ongoing race for market dominance. Against this backdrop, a decentralised global network stands out as an unusual proposition which aims both to capitalise on and to contribute to the popularity of an open standard.

In the case of TTN, one of the central goals of the initiative's coordinators has been to scale up a global low-power network while at the same time allowing for the coexistence of disparate agendas. Succeeding in attaining growth in this contested landscape entails a resolution of the infrastructure paradox or a twofold effort of ensuring long-term stability and allowing for flexible-enough configurations (Star and Ruhleder, 1996). In other words, successfully scaling-up the infrastructure is contingent both on the standardisation of a shared resource and the possibility for contributors to 'tailor' and configuring networks in line with their local needs (Hanseth and Lyytinen, 2003). In TTN, such an effort seems to transcend the scope of manoeuvring of a single entity and instead demands that agency be distributed across multiple spheres of action (I return to this issue later in the chapter).

In light of the challenge of attaining network growth, studies of information infrastructures have sought to capture the options that are available for system builders and architects to enable and influence the evolution of networks (Hanseth and Lyytinen, 2003; Monteiro *et al.*, 2013). To this end, it has been helpful to recognise the dynamics of network growth and the problems that arise in the long term when dealing with the tension between flexibility and stability (Hanseth, Monteiro and Hatling, 1996). A common approach to explaining growth has been to draw on concepts from network economics, notably positive network externalities and lock-in (see Arthur and Arrow, 1994; Shapiro and Varian, 1998). In the next subsections, I discuss how these two effects are brought to bear on the strategic decisions made within TTN.

Positive network externalities

Economists have used the term positive network externalities to refer to the idea that the value to each user of a network increases with its 'popularity' or the number of users already on board (Economides, 1996; Star and Ruhleder, 1996; Shapiro and Varian, 1998; Hanseth and Lyytinen, 2003). Further adoption of a standard is thus driven by the number of users that have already adopted the standard, and this, in turn, attracts more users. As a larger base forms, more products and services are added, and the credibility of the standard also increases (Liebowitz and Margolis, 1994). Moreover, these effects could be intensified by the possibility of a network reaching a critical mass, or a tipping point after which it should be able to 'grow by itself'. The effect of this momentum is often explained as a virtuous cycle whereby new users have an incentive to join due to the high benefits and the low risks involved (Liebowitz and Margolis, 1994; Shapiro and Varian, 1998).

In the case of TTN, LoRaWAN was adopted as the primary communication protocol underpinning decentralised low-power networks. The open LoRaWAN specification was promulgated in 2015 by a consortium of large industrial firms (the LoRa Alliance) with the goal of facilitating interoperability between vendors and network operators. At the core of the open specification was the need to facilitate innovation: 'While the specification defines the technical implementation, it does not define any commercial model or type of deployment (public, shared, private, enterprise) and so offers the industry the freedom to innovate and differentiate how it is used' (LoRa Alliance, 2015b). The flexibility of LoRaWAN has allowed for different models of implementation such as operators offering network subscriptions and commercial services, privately-owned networks and open communities of developers as in the case of TTN. Over the years, the popularity of the LoRaWAN specification has profited from (as well as helped to) the growth of TTN which could be measured in terms of the aggregate number of members gateways (Figure 14). The absence of a business model behind decentralised community networks is explained by the coming into play of positive network externalities. Or, the assumption that the benefits of the overall increase in the adoption of the LoRaWAN standard outweigh the costs of subsidising certain components of the infrastructure.

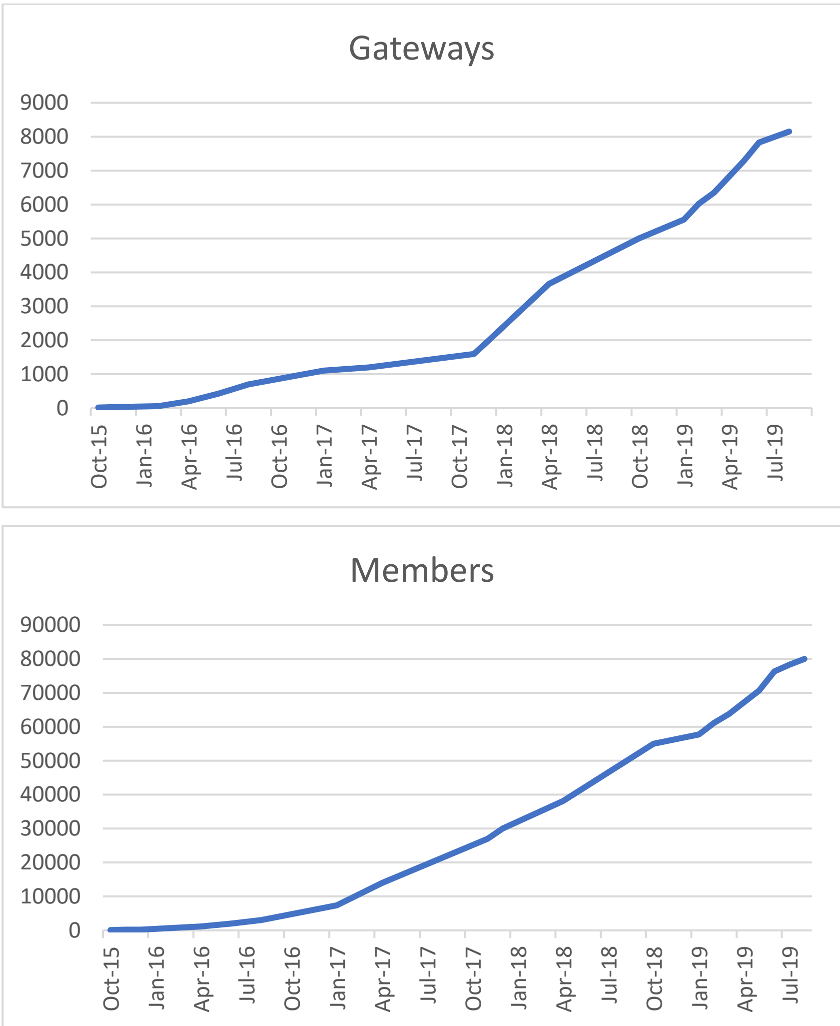

Figure 14: Members and gateways growth 2015 - 2019

Lock-in and path dependency

The possibility for lock-in and path dependency are crucial concerns to those involved with the construction of low-power networks (LPWANs). Lock-in risks arise as more users adopt a standard and more information and knowledge are accumulated around it which makes it increasingly difficult and costly to switch to an alternative standard (Shapiro and Varian, 1998; Hanseth, 2000). Relatedly, as networks grow and stabilise over time, they become more resistant to change which could complicate adaptations to future requirements (Liebowitz and Margolis, 1995; Hanseth, 2000). In the case of LoRaWAN networks, not only software-based components are designed under the definitions of the standard, but also base stations and end-devices. Opting for a LoRaWAN network in this sense carries a commitment of investment in critical elements which are not compatible with other LPWAN options. Ensuring the overall base of LoRaWAN users grows therefore comes with high cost lock-in implications for users.

At the same time, users may be locked-in to a specific LoRaWAN operator if mechanisms for interoperability are not put in place. Reducing the risk of this type of lock-in has been a central design consideration within TTN. Indeed, efforts to ensure interoperability with other network operators and allowing actors to freely replicate and reconfigure the network software through open-sourcing have been important mitigating factors to possible lock-in effects. This was nicely illustrated by one of my informants:

> So, let's say tomorrow TTN gets bought by Microsoft for example or Google or ZTE, these are three different companies that would cause three different political problems in the organisation. If TTN would go bankrupt that would cause a different problem. When I started the organisation, I said all this stuff is open source, so if something happens with TTN we'll just build a parallel network and we go back to it. (Interview with initiator from New York, August 2018)

As of now, the race of standards in the LPWAN market is still ongoing. This adds up to the risks attached to IoT investments and calls for cautious approaches. The high degree of autonomy that is afforded to contributors could, in fact, be at odds with the trajectories envisioned by TTN coordinators as local actors hedge their bets based on the evolution of the IoT landscape. This is evidenced by the different future-proof strategies developed by peripheral actors to grapple with the risks of lock-in:

> We officially traded our name 'Omnia Connexia' Flevoland. Which is Latin for connect everything in Flevoland. And we did that on purpose, not to bound ourselves with our names to the Things Network. Because we all can expect that the LoRaWAN technology two years from now is nothing. I don't know, I'm predicting but that's our world. So maybe it's Sigfox in two years, I don't know. Then from a foundation perspective there's no problem. We are still the human network of people that are interested in doing IoT (Interview with Initiator from Flevoland, March 2017)

> It is clear that TTN is used because suddenly we have a new technology that allows solutions to problems that were previously difficult or expensive to solve. Many people join TTN without knowing what LoRaWAN is at that moment and then they begin to explore LoRaWAN and they get to know it. If tomorrow we have another technology, these people will have the same motivation to migrate to that technology or complement what we already know with this technology. So I think that TTN has fostered a community, of course there will be people with commercial interests with LoRaWAN but also more open people who are willing to use other technologies when they arise, in fact it is not unusual in the forums of TTN to see people share their ideas even if they are not directly related to LoRaWAN. (Interview with initiator from Madrid, October 2018)

Looking at the economics of networks is a good starting point as they reveal key issues to be considered by the core group and peripheral actors in regard to scaling up the network and committing to infrastructure investments. However, drawing merely on the aggregate of members and gateways comes at the expense of glossing over the uneven patterns of network scaling up at different locations. In the case of TTN, the success of the global network seems to be intricately contingent on the work carried out at the local level. It is thus necessary to look into the various manifestations of such work and their implications for global growth.

Facets of heterogeneity

Building on concepts from the information infrastructures literature (Aanestad and Hanseth, 2002; Hanseth and Lyytinen, 2003), in this section I analyse two different facets of heterogeneity within the TTN ecosystem in order to arrive at a micro-level understanding of the problem of growth in the context of decentralisation. Based on some of the responses from my informants, I draw attention to the specificities of local practices, people's motivations and forms of organisation. First, I start by exploring the various individual motivations behind the involvement of peripheral actors and discuss how they might collide and complement in the pursuit of collective outcomes. Second, I delve into the process of bootstrapping of local networks and communities and discuss how deadlocks have been variously overcome through different forms of social organisation.

Individual preferences and motivations

In TTN, local implementations are shaped by the preferences of community members. Across the board, community members have diverse motivations and interests which are contingent on the local culture, politics, economic situation, knowledge and professional backgrounds. As shown in the taxonomy of actors of Chapter 5, local social formations are driven by different impetuses which are not merely economic and professional. Some of the members for instance are driven by curiosity, an interest in learning and knowledge sharing knowledge, recognition, a sense of accomplishment, the need to solve specific problems in their community, or sheer pleasure in technical practices. These motivations seem to resonate with those found in studies of open source software development (Hertel, Niedner and Herrmann, 2003), not least due to the fact that many members are well acquainted with the politics and culture of open source projects. Equally so, motivations also point to moral aspects that relate to the potential of open technologies to democratise access and empower people to own and operate data networks which have been found in wireless community networks (van Oost, Verhaegh and Oudshoorn, 2009; Söderberg, 2011). In Table 5, I list some quotes from my informants detailing their reasons for partaking with building a local network in the TTN ecosystem.

Table 5: Motivations for starting TTN communities

Interview No/Role	**Quote from informant**	**Key words**
2 / Initiator from the Netherlands	'...that is the whole reason why we started it and the whole way to make this technology more accessible and more used and cheaper and better is by making it as easy as possible to experiment with it'	Democratisation, Sense of accomplishment, curiosity
4 / Community member from the Netherlands	'We've got to help, because it's community-driven. It's really at the core of the infrastructures you would need or could use to stimulate this sharing of skills and knowledge and experiences. So that has been at least my	Democratisation, Sense of Accomplishment, Community

	focus, not necessarily to use the network or to build killing applications or services on top of this network.'	Empowerment, Learning
13/ Initiator from the Netherlands	'[my goal is] to have coverage in my local vicinity and then be able to do experiments with real applications of LoRa in the public space and that benefits the municipality and the province and me because I then I get paid for doing it.'	Experimentation, community benefit, professional interest
12/ Community member form the Netherlands	'… [the community initiator] really believes in the smart citizen subject, so getting people involved in technology. And her thought was that the things network was the way to get people involved. The main focus was getting people involved in the smart citizens' world'	Community benefit, community Civic participation and empowerment
8/ Initiator from Zurich	'By the time the new gateways started working, the entire community process skyrocketed significantly. That is something I repeat in each presentation, there is a very great inertia. If one reads this says very well but it is hard work to do it then I will not do it, and nobody does.'	Community benefit, professionalisation
9 / Initiator from the UK	'I perceived the potential of the things network. This idea that its model is distributed, everyone can use it and you're creating a commons-based infrastructure … So, it was this idea that by doing it this way, it could be inexpensive resilient and ultimately democratic'	Democratisation, Community empowerment, sense of accomplishment
11 / Initiator from the Netherlands	'I'm there for helping out people to innovate, not to help people to commercialize it. If they can do it, I wish them luck, it's good for them.' Lennard – Flevoland	Experimentation, learning, community empowerment
14 / Initiator from New York	'…of course, I need to make money. But to me the positive, the thing that is transformative about this technology is that we can make remote sensing available to everybody and do an adaptation that force the rest of operators to be honest. So, if they're going to use a commercial operator, they can do a proof of concept with the Things Network and then pay somebody to do stuff. There are so many ways that things can go. What we have to do is to make it possible'	Democratisation, Community Empowerment, Professionalisation
6 / Contributor from Canada	'I guess to make it sustainable and to have a community of people who are knowledgeable and contribute.'	Learning, Community Empowerment,

10 / Initiator from the Netherlands	'... to know what we have to do and try to find out how the technology works. So, it was more curiosity-driven'	Curiosity, learning, experimentation

A range of different motivations coalesce in local assemblages and give way to difficult negotiations, alliances and divergences. Disparate or incompatible motivations for instance lead to problems of coordination which manifest in disorderly implementations. While a higher number of contributing members within a local community could, at least in theory, allow for the provisioning of more shared infrastructure and better coverage, uncoordinated efforts could also lead to haphazard and inefficient deployments. This issue has been salient particularly in early-stage communities and non-commercial groups where the disorganised installation of gateways has resulted in inefficient deployments.

Indeed, the most obvious or technically feasible location for an individual to install a gateway is not always the best in terms of collective benefit. In some cases, this issue motivated a push for institutionalisation and stronger coordination among members in some locations. In the Madrid community, for instance, a combination of gateway management and collaboration with other actors was seen as a possible way forward:

> What we are trying to setup through the community here in Madrid is a system by which the Community acquires the gateways, so they are installed in very favourable locations, at very high points. And this we are trying to organize through Internet providers some of which give Wi-Fi connection to communities that are remote or that do not have good coverage of fibre optics [...] On the other hand, we are also trying with the amateur radio community that already have really unique sites here in Madrid on high mountains for repeaters. [But] it is not something widespread at the moment. Right now, anyone who wants to buy a gateway, installs it and maintains it himself. (Interview with initiator, October 2018)

Some actors have brought in existing stocks of knowledge from their previous experiences in communities of practice such radio amateurs, open-source software or wireless community networks. While their existing technical and organisational knowledge played an influential part in shaping the efforts around low-power networks, schisms and diverging agendas also led to the formation of different sub-groups coexisting in the same city or locality. This further complicates the efforts of coordination giving and the possibility for harmonising network deployments and improve their quality. Conversely, the heterogeneity in terms of knowledge and skills also allows for complementarity insofar as not all actors carry out the same work. While some are more knowledgeable about the implementation and maintenance of network elements, others take part in complementary tasks such as hardware design, application development or business-oriented activities.

Local bootstrapping of infrastructure

Bootstrapping is a common term in the business jargon and has explicitly been used by TTN founders to emphasise on how the initiative was started as a collective effort without relying on external investors: ‘When we started the things network, we started with version 0, it was really bootstrapping. We released this a few weeks after Wienke and I had our first brainstorming about TTN’ (Stokking, 2018b). As described in chapter 5, the inception of TTN involved the creation of a pilot community in Amsterdam and an effort of persuading the first contributors. The project coordinators carried out these initial activities without resorting to external investment and instead advanced the idea of crowdsourcing the deployment of the network. Some of the costs were covered by the founders, while the rest of the components were sponsored by a handful of local firms. The first wave of adoption ensued with communities getting kickstarted in different locations. The first members to get on board were highly motivated individuals who became invested in the project and took up the responsibility for building local implementations. Local groups were however equally confronted with the challenges of deploying and validating the network and persuading new members to join. In this sense, local communities too underwent a (second order) process of bootstrapping shaped largely by the local conditions, for example, the track of experience of their members, their culture and their socioeconomic backgrounds. The particular ways to go about bootstrapping is in many respects far removed from the contexts and coordination ability of the core group. As recounted by an initiator:

> So, the first thing was, a lot of people came a lot of people wanted to collaborate and we opened up the Slack group and started organizing meetups, started connecting with other communities, started building stuff. We also held a meetup where people actually built a sensor. And that was the way to bootstrap the community. (Interview with community initiator from Enscheda, March 2017)

Not only deploying an initial network calls for significant resources and effort but overcoming the challenge of starting a network from scratch entails ingenious design strategies (Monteiro *et al.*, 2012). For the case of LoRaWAN networks, this process involves the replication of the network software needed and the commissioning of gateways, antennas and other complementary elements to connect to nodes. In TTN, non-commercial initiatives, in particular, face both the need to secure resources to kickstart the network and the challenge of persuading an initial base of volunteering contributors. In conversations with local network implementers, they often reported being confronted with a 'chicken and egg' dilemma at the time of kickstarting local communities: whilst new members needed to be enlisted to crowdsource a network, this task was strikingly difficult in the absence of a concrete product to showcase the benefits of the new technology, particularly to individuals with little technical knowledge. Early in the formation of communities, informal meetups were ideal spaces to spark initial brainstorming and for attracting potential members. These events offered opportunities for initiators to go in detail about LoRaWAN drawing mostly on generic examples and successful implementations elsewhere. Yet, an initial network seemed imperative to explore the utility of the technology with local and relatable applications.

> …it's a chicken or an egg problem you have to have coverage, but you also need to show applications. We had limited funding to develop the two projects. (Interview with initiator from Den Bosch, February 2017)

> So, it's a chicken and egg. You have to have a network so you can actually do this stuff. So, what we've found is that we switched from developing things that can connect to actually build that network infrastructure. (Interview with initiator from the UK, July 2017)

The deadlock experienced by local actors was not news to TTN coordinators. One of the community managers described this problem as a 'network paradox' which was variously dealt with by local members by, for instance, liaising with business or public institutions, or by subsidising or assembling the first instance of the network. Particularly for non-commercial groups, the solution was to deploy an inexpensive initial infrastructure, which served both as a 'test bed' for use cases and as an educational platform to tackle the knowledge barrier for new entrants. Such incipient networks would be used to demonstrate its use and to attract more members and volunteers.

> … okay let's first provide the network, let's make sure that there is a network and a group of people that understand how it works. Then we're going to push up all the entrepreneurs in the environment and now we're trying to make sure that we can actually effectuate the business case. (interview with initiator Flevoland, September 2017)

The construction of the decentralised networks in TTN underwent not only a first moment of bootstrapping, but further (second order) instances of bootstrapping as local networks were built anew following distinct trajectories and motivated by a diversity of local needs. The work of building local networks in the TTN ecosystem involved not only a great deal of learning and experimentation but also mechanisms of coordination and management of resources. The challenges surrounding the kickstarting of networks were dealt with through various social formations and organisational structures at the local level. As described in Chapter 5, not all local communities established formal organisation and, in fact, some deliberately eschewed such attempts due to difficulties in reaching consensus between members, a lack of resources or legal limitations. Yet others experimented with different institutional styles and formats and various levels of formality including, for example, non-profit organizations, associations, cooperatives, foundations, research groups and private ventures. For certain local groups, some level of institutionalisation was seen as a crucial legitimising mechanism to attract funding and buy-in and to establish contractual relationships with third parties.

Back in 2016, in a forum thread titled 'Creating a legal entity to support the community network', a community manager at TTN drew attention to the creation of the first official legal entities:

> Different communities are setting up non-profit associations to cover legal matters, to improve a community's professional appeal and/or to create an entity that is responsible for maintaining the network. (Slats, 2016b)

Forum users further commented on their efforts to establish legal entities of different sorts:

> After initiating TTN in Sao Paulo, Brazil, the group of people working with me here (such as @lviola, @desmarins, @engvidal) decided to create a non for profit Internet of Things National Association (called ABINC - www.abinc.org.br). This association has a bigger scope today (foster and promote IOT in general in Brazil) and TTN is one of the strategic projects under the legal umbrella of the association. ABINC is also in process of affiliation to the Lora Alliance in order to establish a direct channel of cooperation with the Alliance, but the idea is to be an agnostic association and not exclusively tied to any technology. (Maeda, 2016)

Of relevance, is the case of the Zurich community, one of the largest and most active localities in TTN, where the process of institutionalisation was 'open-sourced' as a means to help other communities to replicate the model.

> Last week, we finally founded the civil association to support TTN communities in Switzerland. As discussed in other channels, we will open source all the documentation that might help other communities do the same in other countries, and we're starting with the "Articles of association" (statutes), check out our github repo: https://github.com/open-network-infrastructure/ (Casas, 2016)

Distributed infrastructuring

I have so far outlined the difficulties surrounding the growth of decentralised low-power networks. A look into the different dimensions of heterogeneity sheds light on the challenges of imagining and building a global network through the dispersed and disparate contributions at the local level. At the same time, the high level of variability in the ecosystem brings about a tension between the short and long-term visions of different actors and thereby the extent to which control is exerted by the initiative coordinators in their effort to foster growth.

In the case of the Things Network, infrastructure work has been distributed among core and peripheral actors. While the former group have centred their efforts in building a generic and modular network architecture, local actors have been delegated with the task of building and operating local configurations based on their specific preferences, modes of resource allocation and organisation of work. A modular architecture and its embodiment in software constitutes the prime technical baseline aimed at enabling the work of dispersed network implementers. In this scenario, no single group seems to be in a position to steer the growth of the global network beyond their local scopes of influence. Instead, growth comes about as a by-product of the dispersed work of contributors. The process of coming to terms with the tensions brought about by the global data infrastructure project can be described as an instance of *distributed infrastructuring*.

The verbalised form 'infrastructuring' (or 'to infrastructure') is a helpful analytical device to emphasise both the diversity of work practices surrounding infrastructural systems and their obdurate/ongoing status (Karasti and Baker, 2004; Star and Bowker, 2010; see also Chapter 3). Infrastructuring has been used widely within participatory design and CSCW as a way to foreground the conflation of the practices of design and use but also of other facets of infrastructure work such as implementation, modification, maintenance and redesign (Karasti and Syrjänen, 2004; Pipek and Wulf, 2009; Karasti, 2014). Infrastructuring is a helpful analytical tool here as it falls in line with being cautious about the use of preconceived roles (designers, users) in favour of a focus on practices (designing, developing, architecting, implementing, maintaining, etc).

In a similar way, I deploy infrastructuring to emphasise on the manifold types of work undertaken within and between heterogeneous communities involved in the implementation of functional systems. The modifier 'distributed' in turn alludes to the spatially and temporally spanning character of infrastructure work. This means that acts of infrastructuring are not only relevant within the boundaries of a local network and project but are of broader (regional and global) significance. As such, distributed infrastructuring can be defined as *the process of collectively building extended and heterogenous information systems through the work of geographically dispersed actors operating without explicit consensus and with common/standardised technical means*.

In order to illustrate the contours of the notion of distributed infrastructuring, it seems helpful to unpack the way tensions and dilemmas have been dealt with in the TTN ecosystem. First, I look at the spatial dimension, in order to problematise how the global and local scales of infrastructure have been imagined and realised. Second, I look at time; I delve into the disparate ways in which peripheral and coordinating actors deal with the short and the long term. Third, I discuss how the problem of control has been approached by the project coordinators and what strategies have been tried out to achieve their goals.

Global vs local dimensions

As discussed at the beginning of this chapter, describing infrastructure in relation to work practices is a helpful bottom-up approach to arrive at the global level through an understanding of the local level. While thinking about the global reach of infrastructures might be valuable for many uses (e.g. long-distance telephony, telemedicine, email), much of the interface between users and systems has a very local meaning. As Pipek and Wulf rightly illustrate (2009, p. 456): ‘Modern railway transportation networks, for example, span countries and even continents, but how important is that to a commuter who lives in Bonn and works in Siegen, about 60 miles away?’

An analogous observation can be made in the realm of low-power networks. While global LoRaWAN coverage has been touted by the LoRaWAN alliance, applications for sensors very rarely rely on the possibility for international connections. Apart from a few use cases (e.g. supply chain tracking), most use cases seem to be driven by highly local and context-specific needs (e.g. smart parking, smart irrigation systems or air quality monitoring). The rollout of most local LoRaWAN networks is largely dictated by the specific problems that they address and shaped by the available range of expertise and resources, the topographic constraints, the existing installed capacity, and the local institutional landscape. Similarly, network implementations may also be purposely built as self-contained private deployments. As it has been explicitly stated by the TTN coordinating team, the architecture enables the implementation of networks which could be isolated from the public-facing global network. Although private networks are supported by the same underlying architecture, their data traffic remains confined within the boundaries set up by the network implementers. There may be legitimate concerns of security and privacy behind such implementation choices, as in the case of systems of people counting or monitoring of movement at a train station or an airport, where data may be considered to be highly sensitive.

In the case of TTN, the global dimension of the network emerges rather as an abstract aggregation of fragmented and disparate sub-networks which are not necessarily interconnected. The global and local dimensions of the network are nonetheless interdependent. While the purview of a global network emerges as a result of the construction of local networks, positive network externalities stemming from the wider adoption and credibility of the standard facilitate commercial ventures and local infrastructure work owing, for example, to the increased availability of learning resources, peer support and knowledge exchange, and the collective improvement of opensource network software.

As discussed earlier, the universe of actors within the TTN ecosystem is highly diverse, and local formations are themselves heterogeneous assemblages with varying constitutions, technical acumen and modes of organisation. The relationship between the local and global dimensions shows that while local formations carry out infrastructuring rather autonomously, a shared and generic architecture is needed. Distributed infrastructuring entails, in the first place, the work of geographically dispersed actors working with a common technical baseline and acting without the need for consensus, oversight or supervision mechanisms. In this landscape of distributed agencies, those actors located at the centre (i.e. project coordinators, network architects and core developers) fulfil the critical role of *orchestrating* a global infrastructure through the use of boundary objects and a range of design choices and strategic decisions aimed at enabling communities to implement local networks.

By and large, one of the most critical boundary objects used by core-developers in relation to the broad universe of contributors has been the depiction of a flexible and modular network architecture. The architectural diagrams have been continuously a central device for communicating various aspects of the decentralisation strategy, such as the 'separation of concerns' principle, the logic of scaling up, and the different functions of modular components. However, other mechanisms of alignment such as shared repositories and strategic alliances are also part of the repertoire of activities of orchestration. Some of these include:

- An interface for peer support and knowledge exchange
- A shared knowledge base of documentation and resources
- A global registry of members
- A global inventory of the installed base[31]

[31] While using gateways as a proxy is a way to create global inventory of the installed base, its validity is limited by the fact that some networks may be private and not counted in the statistics.

- An agenda to drive down the cost of implementation through intermediaries such as vendors and manufacturers

The articulation of a global network through the work of core and peripheral actors is enabled by mutual learning. As shown in Chapter 5, community managers at TTN play a central role in facilitating knowledge exchange by performing liaising activities aimed at gathering feedback from members about local social dynamics that informs decision making. Through this interaction it is possible, for instance, to identify blind spots in the ecosystem; inactive communities and proven strategies; business opportunities and strategic alliances; and enable the circulation of this knowledge in the ecosystem.

Grappling with different timeframes

The second aspect of distributed infrastructuring concerns the longevity of infrastructure. Since the inception of TTN, a constant challenge for coordinators has been to make networks durable by ensuring both a committed membership and a technically-sound network backend. Core-members routinely devised and updated plans of action in quarterly and yearly roadmaps which included milestones for technical and strategic functions. The short and long-term thinking of the core team is however far removed from that of peripheral actors who deal with a different set of technical and organisational challenges. The highly heterogeneous array of dispersed actors also gives way to a diversity of temporal framings and definitions of short and long-term objectives. Local communities, for instance, organise their short-term duties around specific projects (e.g. prototyping a use case or organising technical workshops) and depending on the frequency of face-to-face meetings and the time commitments of their members. Conversely, full-time staff at TTN carry out software development, community management and other activities in a daily basis following more structured processes and within comparably shorter development times.

Differences are also salient in the way different groups grapple with the long term. Local groups, on the one hand, may or may not abide by a long-term roadmap (e.g. beyond 3-years) depending on their specific organisational structure, their business models and their time commitments. While small groups would be content to 'ride the wave' of LoRaWAN and the evolution of TTN, more stable communities or private ventures engage more actively with the long-term by, for example, taking into account considerations of risk and lock-in in anticipation to the emergence of new technologies. A case in point is the community in Zurich, where long-term thinking contemplates the possibilities that lie beyond the realms of TTN and LoRaWAN:

> …although we are now focused on LoRaWAN, eventually LoRaWAN will be replaced by other technologies, therefore the goal from now in 5-10 years-time is not only being an association that supports LoRaWAN but an association that supports the movement of open networking in general. Interview with Gonzalo Casas, initiator Zurich

On the other hand, core developers formulate yearly roadmaps to guide their work and construct future visions of a global network spanning over an indefinite long-term horizon. The espousal of a standard, however, has implications for their long-term planning insofar as the trajectory of TTN is contingent on the success and survival of LoRaWAN as a LPWAN standard. Although this is a matter that escapes the temporal scope of this study, the response from one of the founders of TTN was that 'there is no reason why [TTN] cannot include other RF technologies' (Griezman, 2019).

It is useful at this stage to map the different activities and temporal frames between the core team and peripheral actors. In Table 6, I outline these mismatches in terms of two temporal orientations: project time and infrastructure time (Karasti, Baker and Millerand, 2010). For this analysis, infrastructure time refers to the work aimed at sustaining and growing the infrastructure: it incorporates short and long-term acts of infrastructuring such as maintenance, monitoring, upgrading and learning. Project time, in turn, encompasses the work that is carried out towards fulfilling discrete projects with a defined time duration. The project-oriented temporality can be seen as bearing upon those activities that are supported by the infrastructure. Local groups, for instance, engage with the development of applications, prototypes, experiments that use the infrastructure or commercial ventures that exploit the affordances of the existing infrastructure. Core members at TTN also engage in complementary projects such as the commercialisation of LoRaWAN expert services, professional support and the provision of hosted solutions.

Table 6: Different activities and temporal frames between communities and core-developers

	Core members	*Peripheral actors*
Infrastructure time	Activities: Universal network monitoring, global scaling up, growing members, back-end stability, iterations to the backend, 3rd party integrations, documentation Timeframe: standard lifetime	Activities: local network monitoring, city-wide scaling up, institutionalisation, redesign, learning and knowledge exchange Timeframe: contingent to the community, e.g. standard lifetime, infrastructure lifetime, 10+ years
Project time	Activities: consulting, hardware and application development, business implementations, business partnerships Timeframe: duration of the project, 0-1 years	Activities: prototyping of use cases, commissioned projects Timeframe: duration of the project time, 1-3 years

For both core and peripheral groups, complementary projects enabled by the infrastructure constitute a means for network growth and long-term sustainability. In the absence of obvious financing mechanisms for this 'mode' of infrastructuring, contract-based work and commercial spinouts are tried out as promissory paths. In the case of core members, the resources that their commercial efforts generate subsidise the work of improving and maintaining the software components of the global network. Among peripheral actors, the options revolve around private ventures and different mechanisms for financing the operation of networks such as research and innovation grants and membership schemes. Regarding time, the TTN ecosystem subsumes many different degrees of obduracy and attempts to create sustainable organisations. Some communities are seemingly more successful and stable judging by their size, installed base and institutional linkages. Others remain intentionally bounded to discrete deployments and in the absence of sustainable sources of funding and time-commitments, there is a risk of them stalling and disappearing. To cite a recent interview with one of the founders: '[Sustainability] will more and more depend on the business networks that join. They will bring the next wave.' (Griezman, 2019).

Who controls the infrastructure?

Finally, a pressing question brought about by heterogeneity is that of *who is in control?* Studies of corporate work-oriented infrastructures have foregrounded the technical and organisational limitations faced by managers when attempting to accommodate different (and sometimes diverging) agendas in the operation of information systems (Ciborra and Hanseth, 1998; Ciborra, 2000). As observed by Ciborra and Hanseth, 'the governance of infrastructure is a problem, not a given, since there can be multiple stakeholders with conflicting interests. The outcome is that the infrastructure can expand and grow in directions and to an extent that is largely outside the control of any individual stakeholder' (1998, p. 310).

Far from being a straightforward issue of strategic management, locating the opportunities for control is a central problem of distributed infrastructuring. In the case of TTN, the ever-growing number of disparate contributors seems to dilute the options available to network designers and architects to steer the trajectory of the initiative thereby rendering the overall endeavour increasingly unpredictable and uncontrollable. While core members play an important role in ensuring the technical operation of the network and importantly shape long-term discourses and influence the driving down of costs barriers, they have little say on how work is organized locally. In this sense, distributed infrastructuring implies a *deliberate* distribution of agency and control among actors dispersed across the network. A modular architecture in this case affords a high degree of autonomy by communities as a trade-off with core developers' centralised control. This has been a key design strategy embraced by the core group whereby peripheral actors in the ecosystem are expected to act autonomously by owning and operating networks in a decentralised fashion.

To deal with uncertainties of scaling up under these conditions, the core group has adopted different tactics such as the establishment of strategic alliances with advanced actors. The idea of 'regional clusters' in this sense, has been an attempt to ensure the orderly decentralisation of network components (e.g. network servers, application servers, join servers) by organisations working in close coordination with the core team. In the words of TTN's technical lead:

> The free public network our flagship service, currently runs 6 clusters, the Things Network foundation operates EU, US, Brazil and Singapore, then there is the Swiss Open Network Infrastructure Association that runs a public network region in Switzerland, and finally Mesh in Australia operates a public TTN cluster. […] we will be expanding gradually to UK, South Africa, Japan, China, Russia, India, more US, more Europe, so we have ongoing conversations with partners here, we are also still requesting proposition from the TTN

> community, and this is really adding public clusters to the public network. (Stokking, 2018b)

The cluster-oriented organisation of functions resembles the star topology of LoRaWAN networks whereby key components are located as central nodes (Figure 15). Although a modular architecture affords peripheral actors the possibility to deploy any network component locally, it makes economic sense to share common resources which is particularly advantageous for new entrants. Regional clusters are constituted by more committed groups that have been bestowed with the responsibility of operating network elements locally in much the same way as the core team. The availability of geographically proximate servers not only improves the resilience of the network but also reduces the latency of messages, a crucial feature for time-sensitive applications. These network elements require higher investment and effort on their operation (compared to gateways), which is why alliances are seen as a way to reduce the complexity and costs faced by peripheral members and improve the quality of the public infrastructure.

In sum, control is only partially exerted by actors involved in the effort to decentralise the construction of networks. Distributed infrastructuring thus implies a distribution of control across the universe of actors and ongoing efforts of negotiating responsibilities and expectations between central and peripheral actors.

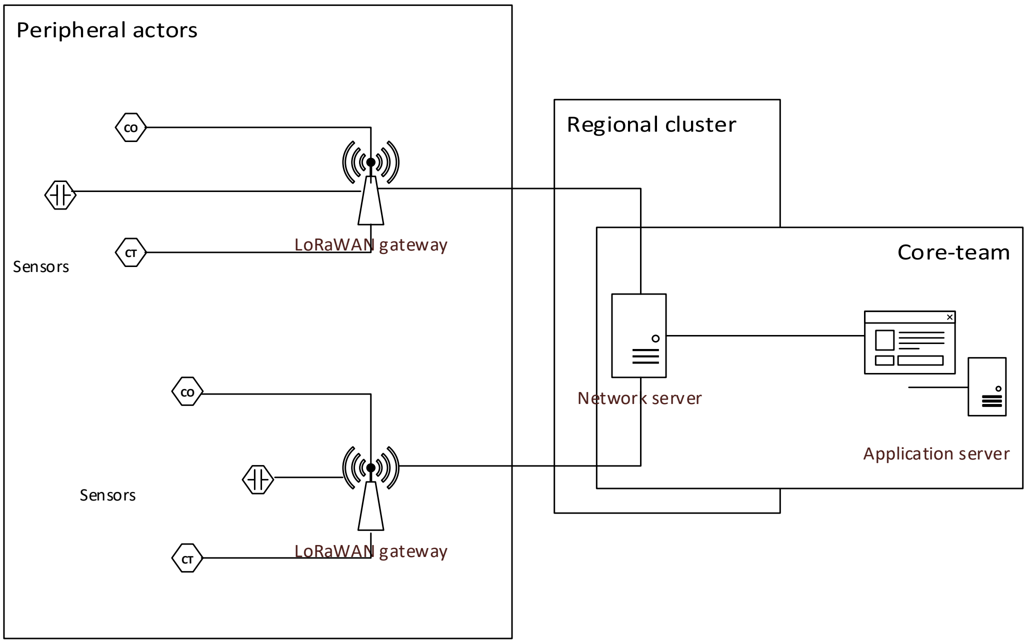

Figure 15: Operation of network functions in the star topology of LoRaWAN networks

Conclusion

In this chapter, I have looked into the infrastructural aspects of low-power networks. Inspired in a relational understanding of infrastructures (Star, 1999; Bowker *et al.*, 2010), I have described the IoT in terms of work practices and sociotechnical relations. This perspective not only runs counter to the traditional view of artefacts being resourcefully mobilised by firms and ingenious designers, but it takes into account the widespread and ongoing nature of infrastructures.

It is crucial to acknowledge that this study unfolds in the midst of an ongoing competition amongst different LPWAN standards. This state of affairs has implications for the way actors grapple with network growth and with the risks attached to investment decisions. Early in the race of standards, TTN pledged to drive the adoption of the open LoRaWAN specification by proposing a model of low-cost distributed deployment. The unique proposition of TTN has been fine-tuned over the years to reduce the risks and costs for dispersed actors and to leverage the positive network externalities brought about by the growing popularity of the standard. Yet, the model of TTN faces a range of challenges. The heterogeneity of actors within the ecosystem complicates the predictability of the evolution of the network at large, as the idea of a global network is contingent upon the diversity of agendas and the haphazard ways in which local actors go about the construction of networks. One aspect of heterogeneity has to do with the distinct strategies adopted by local actors to finance the deployment and operation of gateways. In particular, non-commercial local initiatives face a deadlock while deciding between attempting to recruit contributors to build a network or build a network to attract contributors. This deadlock is variously resolved across the board, which leads to uneven patterns of growth. But heterogeneity is also an issue *within* local formations. Beyond the initial stages of learning about the new technology, the strategies to scale up networks are shaped by the capacity of communities to reach agreements, establish formal legal entities or secure funds. At the same time, the motivations among members could be in opposition leading to schisms and further fragmentation.

In other to capture how tensions and dilemmas have been dealt with in the TTN ecosystem, I have proposed the concept of distributed infrastructuring. Three ongoing issues are useful to illustrate this concept:

1. *The tensions between the global and the local:* The global dimension of the network can only be understood in terms of the local. The construction of a global network is built on the basis of local infrastructure work. The global network, in this case, is conjured up as a rhetorical device to promote the aggregate adoption of the standard and, in this sense, it can be seen (at least for now) as an abstract collection of fragmented local networks.
2. *The disparities of distributed temporalities*: Due to their distinct levels of commitment and forms of organisation, peripheral actors carry out infrastructure work following timeframes that are far removed from those of core-developers. This leads to uneven manifestations of short-term action and notions of long-term sustainability.
3. *The trade-off between flexibility and control*: distributed infrastructuring implies that peripheral actors carry out their activities with a high level of autonomy. In turn, opportunities for centralised steering and control are limited.

Distributed infrastructuring constitutes a collective act of coming to terms with these tensions and dilemmas. For instance, by embracing the autonomy of dispersed actors while ensuring a common means for interoperability; allowing for multiple long-term visions and building the global dimension from the bottom-up. As a generic concept, distributed infrastructuring evokes a process of building decentralised information infrastructures in a rather piecemeal fashion by a range of dispersed groups who may or not be associated and who carry out their work autonomously. This concept may be read as an extended form of infrastructuring insofar as it transcends the scope of a single organisation or project while maintaining a sense of coherence and continuity across separate domains.

Chapter 7 – Making ‘things’ work: Innovation in distributed infrastructures

Introduction

So far, I have traced how a global decentralised infrastructure is constructed by foregrounding the work practices of geographically dispersed actors. A central aspect of this distributed mode of infrastructuring is heterogeneity in its different facets: in terms of social organisation, practices and individual preferences. In this context, actors pursue different objectives and create a diversity of applications and solutions whose specific requirements have implications for the way local networks are imagined and materialised. Notably, in the case of low-power networks, considerations of quality of service and coverage are contingent both on the local physical conditions and the exigencies of the particular applications to be supported by them. An environmental monitoring network, for instance, would differ significantly in its design and quality of service requirements from a ‘cold-chain’ monitoring system. In the first example, a low-density network of gateways would suffice for collecting infrequent referential measurements of air pollution, humidity and temperature from sensors scattered around a city. In turn, monitoring the temperature of goods inside a moving vehicle would require enough network coverage along the supply chain, continuous maintenance and a guaranteed level of network reliability. While the first application could fulfil its function on a free-to-use public network, the second would be better supported by a professionally operated private network.

In the TTN ecosystem, the deployment of local networks is underpinned by a flexible architecture that affords customisation and different topological configurations by autonomous peripheral actors. A modular network architecture, in this sense, is intended to be generic and flexible enough to support any type of application and allow the finetuning of features. Over the years, core developers have continuously refined the network architecture informed by the way peripheral actors make use of it. Infrastructure work and the development of applications and solutions are highly interdependent activities that rely on the successful coupling of the tasks between core developers and peripheral actors.

In this chapter, I deal with innovation as a cross-cutting theme in the construction of infrastructures to address the question of 'how do dispersed forms of work lead to the production of innovations and stable networks?' The analysis builds on the premise that technology is socially shaped and in particular on the idea that technology (and infrastructures), far from emerging out of a process driven by developers and designers for prescribed users, is a collective process (Stewart and Williams, 2005; Williams, Stewart and Slack, 2005; see also Chapter 3; Monteiro *et al.*, 2013).

I begin this chapter by examining the discursive representations produced by TTN coordinators to characterise their target audience: in this case, as innovative developers who are central to the success of the initiative. The framing of *users as developers* calls for a nuanced assessment of the term 'users' which has been commonly applied as a blanket term to refer to a diversity of roles which may be variously implicated in innovation. In the context of the IoT, I delineate a genealogy of the uneven forms of user involvement in processes of change. I then flag the need to account for the contributions of multiple actors in the construction of data networks. To do this, I propose to investigate the processes of mutual learning (Star and Ruhleder, 1996; see Sørensen, 1996) between members of the TTN ecosystem. I continue the analysis by investigating how the outcomes of mutual learning are operationalised through design and strategic decision making. Accordingly, I look into materiality and the affordances of network architectures, physical devices and software development tools. More specifically, I discuss how low-costs, modularity and standardised interfaces have been deployed as strategies to achieve efficient deployments in a decentralised model.

In the second part of this chapter, I schematise a sociotechnical map of TTN, which depicts both the different technical roles and the building blocks that make up the production of IoT applications and solutions. This ecological analysis aims to offer a view of the division of labour within the ecosystem and the way different competencies and technological offerings are coupled through the use of interfaces. I end this chapter by proposing a model of innovation in the context of distributed infrastructures. In this view, I describe how cycles of learning and implementation take place between separate domains of expertise.

Configuring users as developers

As shown in the Chapter 6, in the context of building/sustaining distributed infrastructures, heterogeneous actors coalesce in a collaborative space of action with a range of professional practices. These actors could, in effect, be considered as the primary users of the unfinished systems delivered by core-developers. Yet, some of these actors are expected to actively engage in further infrastructure-building and development activities. It is thus necessary to point out the distinct roles and competencies of these users. For instance, the contributions of some ‘advanced users’ are as diverse as their areas of technical expertise, engaging in critical tasks such as software programming, hardware development, network testing, implementation and maintenance, and various training activities.

These contributing actors are peripheral, or external to the core organisation and may inhabit subject-specific spheres of action. To be clear, the expertise of contributing actors might not only be technical but have domain-specific foci. As the case of TTN shows, collaborating actors link their technical practices and outcomes both vertically within a given field of application and horizontally across different fields and organisations. In this sense, the contributions of peripheral actors can be embodied in the production of IoT applications and solutions *as much as* in the provision of infrastructural components which may be useful in a variety of application domains.

In TTN, innovation has been intentionally organised as a collective process whereby advanced users have been bestowed with opportunities for contributing through the affordances of tools and components. For core-developers, peripheral actors constitute the primary users of their technological offerings, in this case, a network software stack. In turn, peripheral actors engage with complementary activities such as network implementation, application development or system integration, which place them in an advantageous position to become providers for secondary and tertiary users.

Due to the impracticability of harnessing reliable information about users, developers sometimes formulate ideas about users based on personal experience and by using self-referential images and enacting users’ practices (Woolgar, 1990; Akrich, 1995; Oudshoorn, Rommes and Stienstra, 2004). In the case of TTN, core-developers embodied the role of early adopters of the network backend by establishing the very first community that later served as a reference for future deployments. Although the user representations originally formulated by core-developers have changed over time, they still bear the underlying rationale of casting *users as developers*. This representation is salient in the way core-developers refer to advanced users. For example, the real-time count of registered users on the website reads: ‘Supporting 78252 *developers* in building industrial-grade LoRaWAN solutions’ (The Things Network, 2019c). Other user representations used by core-developers include members, partners and initiators.

Over the years, knowledge about users was acquired through various means including ongoing direct feedback mechanisms through collaborative tools, user research, and various engagement activities with organised by TTN community managers. About a year since the inception of the pilot community in Amsterdam, the number of communities scattered around the world neared 250. A user study of the existing universe of registered developers produced a categorisation of five identities (or ‘personas’) who were found in most of the existing communities of contributors. These were: tech expert, business developer, tech entrepreneur, flexible worker and corporate technician (Slats, 2016a). These identities were deemed to play a critical role in the development of local communities, either by partaking in technical implementation and development or by establishing institutional and commercial linkages. This early study, albeit illustrative, was not comprehensive of the universe registered members at the time and focused on contributors with the potential to start commercial ventures. An updated study, for instance, would perhaps include other identities such as academic researcher, student, hobbyist.

The study also contained a representation of the constitution of communities which comprised three levels of involvement (Figure 16). First, a core group, which was in charge of initiating a local community, setting an agenda of work, enlisting new members and organising social events. Second, a base of active contributors, regularly attending meetings and engaging variously with organising the local activities. Third, a peripheral group[32], which represented the majority of members and only interacted occasionally with the rest of the community. Furthermore, a co-design exercise also

[32] This peripheral group refers to the particular level of participation identified in the TTN user study and it is not equivalent to my own analytical category of peripheral actors as defined in Chapter 5.

helped community managers to produce a model of an envisioned path towards successful and sustainable communities. The so-called ‘community maturity model’ consisted of a 5-stage process to start and grow a community by achieving a range of milestones such as establishing a community page, installing at least two gateways and enlisting a minimum number of members (Slats, 2016a). The foreshadowing of how communities were expected to function and grow, served as a model to organise resources and produce templates of how communities should appear. As a result, communities were categorised and sorted, for example, by official and non-official based on the fulfilment of defined milestones (see Chapter 5).

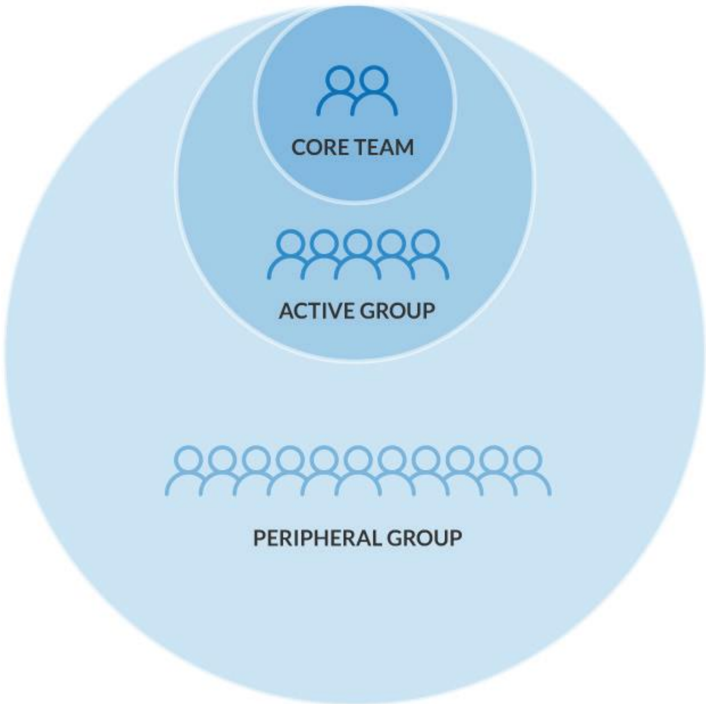

Figure 16: User representation of TTN communities by community managers. (source: Slats, 2016a)

The previous formulations about users informed the development of technical features as well as the drafting of yearly roadmaps. In this sense, core-developers configured their target groups not merely as recipients of technology but as strategic allies and drivers of innovation. These user representations also shaped the vocabulary of the model of decentralisation in the TTN ecosystem. Core developers and community managers applied these categorisations in their discourse and everyday practice: the design of marketing and visual aids and the choice of terminology to address users - e.g. as ‘initiators’, ‘members’, ‘contributors’, ‘integrators’ and ‘developers’.

Mutual learning between heterogeneous actors

> ...we always made strategic decisions based on the actions of users not so much from the discussion. Mostly what we see customers and users do influence our direction not what they say. – interview with Wienke Griezman – January 2019.

As discussed in Chapter 3, innovation in ICTs has been commonly formulated in terms of successful commodified products and services brought about by the ingenuity and efforts of inventors and entrepreneurial actors. This view, however, fails to recognise the work carried out collectively in achieving outcomes and thus tends to overemphasise the role of more visible or influential actors in the process. Innovations have also been largely assessed in terms of their success, which favours market-oriented analyses that may underplay non-commodified, processual and underlying instances of change such as improvements to infrastructure. To deal with innovation in the context of distributed infrastructures, it seems necessary to depart from a Schumpeterian focus on individual inventors and entrepreneurs as the main drivers of innovations to the market.

Social studies of technology have shown that users, far from being passive entities, might importantly shape artefacts through their unanticipated uses or modifications which could, in turn, be captured through different mechanisms of learning. A process of social learning takes place as a result of experience and fruitful encounters between different actors and a range of feedback mechanisms (Sørensen, 1996). The goal of identifying instances of social learning in innovation is to broaden the focus of analysis from just suppliers to other actors involved in technology production (Williams, Stewart and Slack, 2005). This perspective is particularly useful to explain how technical change takes place across different phases of development, implementation and use in the context of infrastructures deployed by heterogeneous actors (Monteiro and Hanseth, 1996; Williams, 2019).

The flow of knowledge between complementary actors in the TTN ecosystem has been a crucial aspect throughout the evolution of the initiative. During the bootstrapping stage, implementers exploit low-power networks mostly for learning and experimenting with the new technology. Subsequently, scaling up is dimensioned by the need to run actual services. During the early stages, the aim is to develop use cases or low-cost validation feats which help to dimension the number of gateways and nodes needed for larger-scale deployments. This process may entail the deployment of local instances of the network software and the prototyping of devices and use cases. At later stages, the focus is on validating applications, conducting field tests to scale up networks and the design, manufacturing and certification of hardware. Throughout the different stages of scaling up and development, the different actors in the ecosystem undergo instances of mutual learning which are facilitated by collaboration tools, training events and documentation.

Three prime learning mechanisms between core-developers and peripheral actors are salient. First, core-developers anticipate potential and existing scenarios with imagined users and applications even when the aim is to create ‘context agnostic’ or generic architectures. Learning through use cases and scenarios is a common way to anticipate and test applications within the technical limitations of the LoRaWAN standard, before committing to massive deployments. This is a cost-effective method to plan for potential hurdles and costs and to engage with peripheral actors. Similarly, at the local level, network implementers and developers accrue vital knowledge about the inner workings of the standard during the bootstrapping stage through prototyping and documentation.

Second, the involvement of the multiple actors involved in distributed infrastructuring is organised by coupling different domains of expertise through different forms of interfacing. In this division of labour, software developers, hardware manufacturers, network engineers, and system integrators establish mechanisms for communication, translation and alignment of their work through knowledge sharing and ‘boundary objects’. In the case of TTN, discrete artefacts and network components are made available in a modular fashion between different spheres of specialisation. The different building blocks in this way and coupled through standardised interfaces (e.g. APIs, GUIs, authentication protocols) or cognitive interfaces (e.g. conferences and workshops) in order to generate a service or product.

Third, different project types call for different network topologies and deployment scenarios which have implications for the strategies for scaling up, financing and establishing an organisational structure. Peripheral actors may, for instance, come up with different tactics to go about funding different projects such as crowdsourcing, research grants, public funding or venture capital. Learning from the way peripheral actors operate locally is crucial for core-developers insofar as it informs strategic decisions and the improvement of the network architecture. This learning process is enabled by means of establishing direct and continuous channels of communication, but also through observation of the use of the network.

As shown in Chapter 6, the TTN ecosystem subsumes a mixture of complementary actors engaging with a shared network architecture while at the same time maintaining a degree of autonomy in the way they implement networks. On the one hand, core-developers are well-positioned to absorb information about the routine practices of peripheral actors and in that way learn about emerging patterns of use and unexpected problems. The outcome of the learning process manifests in how particular designs are favoured in order to enable users to appropriate, configure, combine and distribute them into new and locally relevant configurations. On the other hand, local implementations are informed by situated knowledge about the specific challenges, politics, culture and idiosyncrasies of the local context. Certain functions may require adaptation or translation which are either operationalised locally or reported to core-developers for their implementation. Peripheral members, in this case, are not only network implementers, but hardware engineers, application developers and system integrators. The different types of expert users engage in various cycles of social learning by exchanging knowledge and piecing building blocks together.

In the course of three years, the network backend underwent several iterations and major version upgrades going from v0 to v3 -almost one major version per year. Each iteration built on the knowledge accrued throughout the years by the core team and evolved in parallel with the LoRaWAN specifications to support new features as they were published. The standard developers did not initially devise the LoRaWAN specification for decentralised topologies. Therefore, core developers built a network architecture from scratch with a preference towards modularity and 'separation of concerns'. This design was intended to allow expertise and resources to be mobilised and scaled up as needed. Particularly in the early stages, network implementers and community initiators played a vital role in adopting the architecture to deploy local network instances which were configured to meet specific needs. Incremental improvements to the architecture were incorporated and deployed during this early process of implementation and usage thanks to continuous validation and feedback mechanisms. Conjointly, as shown in Chapter 5, the network software was codeveloped with the help of dispersed contributors who contributed to the opensource repository which received thousands of contributions from external developers. Rather than improvements being unilaterally produced by the core-developers, they arose as a result of strenuous cycles of learning-by-doing and learning-by-using.

An effective understanding of innovation in distributed infrastructures calls for an extended focus on what constitutes innovation. Drawing on the case of TTN, some considerations are salient in this discussion. First, motivations and sociotechnical formations are highly heterogenous and situated. Different verticals, while relying on similar infrastructural requirements, may lead to different network deployment scenarios. Network architects thus need to strike a balance between standard generic functions and flexibility for a range of applications. In this sense, architectural improvements are themselves part of the innovation process and are continuously informed through mechanisms of learning. Second, decentralised network architectures give way to a division of labour whereby interdependent and complementary actors contribute in specific ways innovation. Piecemeal work, such as discrete contributions of code to an open source project, field testing, or prototyping may easily go unnoticed, which calls for careful consideration of the diversity of work practices. Finally, dispersed actors may be confronted with a deadlock insofar as the generation of new applications and services necessitates an existing installed base which, in turn, is driven and dimensioned by the exigencies of applications. As discussed in chapter 6, this deadlock is often resolved through establishing testbeds for experimenting with use cases. Ultimately, ongoing infrastructure work such as implementation, operation and maintenance, needs to be considered as crucial to the development of new products and services.

Operationalising flexibility

In this section, I focus on how change manifests as a result of mutual learning processes and why certain decisions and configurations are selected over others with the aim of ‘encouraging’ users to innovate. To this end, I will look into the materiality of network components as a means to assess how instances of learning are operationalised in the design and development of specific technical features.

As discussed in Chapter 3, various scholars of information infrastructures have invoked the idea of ‘generativity’ to explain the role of key technical features in the generation of improvements or innovations (see, e.g. Bygstad, 2010; Nielsen and Hanseth, 2010; Monteiro *et al.*, 2013). Although the term suffers from multivalent uses and it is seldom explicitly fleshed out, the following definition is often cited: 'Generativity denotes a technology's overall capacity to produce unprompted change driven by large, varied, and uncoordinated audiences' (Zittrain, 2006, p. 1980). The argument for information technology as generative is developed from different research traditions: critical realism and interpretivism (see Chapter 3). However, both approaches give relevance to the question of how different degrees of flexibility in information technologies influence how heterogeneous actors appropriate, configure, repurpose and combine technological offerings. At the same time, flexibility is necessarily bounded, not only by the material features of artefacts but also by the specifications of standards, the conventions of practice or regulatory regimes

In order to dig more deeply into what renders artefacts and infrastructures generative, I propose to underpin generativity on a vocabulary of affordances (as a relational concept) rather than on the descriptions of specific attributes, properties or functions. In doing so, the goal is to trace how actors involved in the development of infrastructures operationalise their decisions and the knowledge accrued over time through communicating their intentions, enabling flexibility in technical designs, constraining undesired actions and lowering the costs of implementation.

Costs of involvement

The low costs of associated with the implementation of low-power networks have been central in the agenda of TTN core-developers. Throughout the years, a range of resources has been put in place to aid learning and lower the cost barriers for peripheral actors. Three factors can be mentioned in regard to the costs of involvement. The first one concerns the cost of hardware. One of the most effective ways of intervening in the reduction of costs was through taking an active part in delivering low-cost hardware alternatives to those available in the market. Making network elements affordable allowed the involvement of a broader base of actors beyond large firms and corporate actors and eased the process of learning and prototyping. Even before the delivery of low-cost hardware, communities implemented experimental networks through the use of self-assembled gateways using hardware development platforms and modules.

A second factor associated with costs was the decentralised model of deployment and the 'public' availability of networks. From the outset, the idea of a 'crowdsourced' open network was underpinned by a cost-efficient network architecture and the possibility to distribute the costs of testing, validating and scaling up. By providing free access to the network software and key resources such as servers, network coverage and collaboration tools, developers would see their cost of development drop. Not only core-developers subsidised some of these resources, but also communities found mechanisms to establish shared experimental testbeds and tools for prototyping through the combination of efforts or external grants and sources of funding.

The affordances of the LoRaWAN specification are also crucial in lowering the costs of development. On the one hand, LoRaWAN has been touted as a flexible protocol which can be used in a variety of deployments. According to the LoRa-Alliance, 'while [the LoRaWAN] specifications define the technical implementation, they do not define any commercial model or type of deployment (public, shared, private, enterprise) and so offer the industry the freedom to innovate and differentiate in how a LoRaWAN system is implemented' (LoRa Alliance, 2015b). On the other hand, the very star topologies of LoRaWAN networks lend themselves to low-cost implementations due to their reduced hardware requirements. The long reach of these networks reduces the overall complexity of new rollouts and the cost of deployment, operation and maintenance as fewer base stations are needed in comparison with other (shorter range) wireless technologies. Similarly, given that long-range connections do not have a 'line of sight' requirement, gateways can be installed opportunistically (e.g. at the top of buildings) without the need for towers. Various community-led and private networks have indeed resourced to such a strategy.

Another important cost factor is the use of the spectrum. As opposed to licensed wireless technologies such as cellular, the vast majority of low-power deployments operate in the license-free portion of the radio spectrum, which means there are no costs associated with the use of these frequencies. Finally, LoRaWAN nodes are ostensibly less complex due to their relatively basic computational capabilities compared to, for example, mobile phones or wearables, rendering them comparably cheaper to manufacture (Al-Kashoash and Kemp, 2016).

Modularity and efficiency

Since the advent of computers and the internet, modularity has been a core design principle in rendering information systems amenable to unprompted innovation while ensuring their stability (Baldwin and Clark, 2000). Modular architectures afford the coupling and decoupling of discrete components or modules without affecting other components or the overall function of the system (Hanseth, Monteiro and Hatling, 1996). In the case of the internet, as well as in other information systems and infrastructures, layered modular architectures have been deployed as a means to facilitate access and adoption by a diverse range of developers and the incorporation of new functions over the years (Abbate, 1999; Baldwin and Clark, 2000; Tuomi, 2006). Recent studies of innovation ecosystems show that a modularity principle has been commonly used to foster relations of complementarity among non-hierarchical actors (Baldwin, 2008; Adner and Kapoor, 2010; Jacobides, Cennamo and Gawer, 2018). Modularity, according to Jacobides et al. (2018, p. 2260), 'allows interdependent components of a system to be produced by different producers, with limited coordination required. While the overarching architecture design parameters may be set by a hub, organisations have a large degree of autonomy in how they design, price, and operate their respective modules, as long as they interconnect with others in agreed and predefines ways.'

Modular designs have also been favoured in the architecture of hardware development tools and building blocks enabling a flexible and cost-efficient coupling of components and practices (Baldwin and Clark, 2006; Bonvoisin *et al.*, 2020). One might look, for example, at contemporary hardware development platforms which are designed to be programmed and combined with compatible modules through the use of standard physical interfaces such as I/O pins. The flexibility of these elements, however, may vary along a continuum of choices ranging from fully generic to function-specific devices. While generic modules are meant to host a range of functions for experimentation and small-scale projects, function-specific terminals have a narrower scope with little room for customisation. Hardware platforms are thus generally used in the early stages for testing and validating use cases, which in turn may inform the design and mass manufacturing of custom-made hardware for large-scale and cost-efficient deployments in the wild.

More recently, IS scholars have observed that the prevalence of modularity in the architecture of networks are a key factor facilitating the alignment of actors in innovation ecosystems insofar as it allows functions to be adapted to different technical needs (Yoo, Henfridsson and Lyytinen, 2010). In the case of IoT, a modular logic in the design and networks and applications entails the assemblage of discrete elements such as sensors, chips, network software and advanced data processing facilities. In this way, modular architectures open a range of options to developers who may belong to different domains of expertise. For instance, devices may be designed to be 'network agnostic' allowing hardware developers to participate in different ecosystems by choosing from a pool of network modules. Another boundary-crossing facet of modularity is the possibility to configure hardware via software, which affords lower costs and knowledge barriers for developers without advanced hardware knowledge. In much the same way, application developers do not need to get to grips with the inner workings of network protocols or third-party services thanks to the use of layered architectures and standardised interfaces.

In TTN, core-developers have applied a modular principle as means to operationalise their intentions. The embodiment of a decentralised network architecture (the network backend) constituted a strategic mechanism to delegate development practices to peripheral actors. A prime intention of core-developers, for instance, has been to facilitate scaling up while keeping infrastructures flexible enough to support innovations and infrastructural improvements. As I described in Chapter 5, the modular network architecture was from the outset associated with the notion of 'separation of concerns'. In other words, network architecture diagrams have been used as key boundary objects to operationalise flexibility and afford an *opportunistic* network implementation to a range of actors. The separation of the instances of routing, user registration, application management and network monitoring was intended to allow the decentralisation of components as networks scaled up and new requirements emerged. This flexible mode of deployment accommodates a diversity of scenarios and technical requirements, for example, in terms of latency, security or network availability. The different modules in the design are coupled between them and with third-party services through the use of standard interfaces such as application programming interfaces (APIs), physical interfaces or authentication protocols.

A sociotechnical map of the TTN ecosystem

In this section, I sketch a map of the different complementary competencies subsumed in the TTN ecosystem in order to trace the linkages between the different types of work practices and technological offerings. To contextualise this analysis, it is first necessary to consider the LoRaWAN ecosystem at large. This broader ecosystem constitutes an equally heterogeneous space for innovation encompassing hardware vendors (e.g. sensors, microcontrollers, chips and other equipment), middleware platforms, cloud service providers, network operators, design and consulting contractors, regulators, public institutions, private and non-profit organisations, standard bodies and developers in various domains and with varying degrees of expertise. Such heterogeneity engenderers myriad transactional and non-transactional relations and a range of innovation milieus commonly referred to as verticals. The TTN ecosystem is, in turn, embedded in the LoRaWAN landscape. In mapping the ecology of actors in TTN, I will focus on the relationships within and between the different sites of action explicitly taking into account the core-team of developers and peripheral actors.

This ecological analysis aims to trace the different paths to producing both provisional as well as finished technological offerings. To do this, I distil the range of technical practices performed by actors at different points of the value chain, from network deployment to hardware design and application development and identify how these practices are coupled. For instance, the primary users of network software might become implementers and developers of value-added technological offerings for other secondary users down the line. In this particular case, implementers appropriate and configure the network software as well as hardware products to either offer connectivity services to another set of users (application developers or firms) or engage directly in the development of applications or services for end-users. Another group of actors in the ecosystem might, in turn, take up the development of IoT terminals by coupling the available network features with building blocks to generate new devices and applications.

Besides the delivery of network services and the production of physical objects, other forms of technological offerings are salient in the realm of IoT. Data networks and sensing infrastructures, in particular, bring about a widespread instrumentalization (or ‘digitisation’) of the physical world which results in the increasing collection of large amounts of data. The focus of innovation thus seems to broaden from commodification to the provision of services based on extracting value from the new sources of data. The delivery of 'solutions', in the jargon of IT practitioners, is an example of such an advanced mode of technological offering. Thus, one can also point to the role of 'integrators' working closely with end-users and assembling different components into a seamless –often referred to as managed—solution. Here lies the ultimate purpose of data networks which rely on the integration of complementary elements in order to harness the untapped value of data. The growing interest in the value of data brings to the fore pressing questions about data control and ownership, privacy and security and in this sense, controlling the means of data collection may also constitute a strong incentive for the adoption of decentralised infrastructures.

Drawing boundaries

To schematise a map of the TTN ecosystem, I will use the metaphor of arenas, which has been a helpful boundary drawing device to deal with innovation-related activities. The idea of development or implementation arenas has been used in STS to refer to both the physical as well as the cognitive spaces where actors, artefacts and standards converge in relation the development of products and services (Jørgensen and Sørensen, 1999; Williams, Stewart and Slack, 2005). The boundaries of arenas are not sharply construed insofar as the practices and memberships of arenas may overlap (Jørgensen and Sørensen, 1999). For this mapping exercise, arenas of development or implementation are described as coherent assemblages of situated knowledge, practices and artefacts pertaining to a specific domain of specialisation.

Four interdependent arenas can be identified in the context of the TTN ecosystem. These are network provisioning, hardware development, software development, and system integration. Arena encompass both the practices oriented to the construction of infrastructure as well as the work towards developing new products and services. Actors located within each of these arenas do not only have technical expertise, but also domain-specific expertise. Ultimately, applications and services arise as a result of actors striving to address local problems through successfully interlinking their competencies and the outcomes of their work. Table 7 shows a list of practices and domains of expertise in each of the four innovation arenas in the TTN ecosystem. This typology serves as a basis to map the different types of relationships between actors in the TTN ecosystem, as there may be overlapping practices and blurred boundaries between these arenas.

Table 7: Implementation and development arenas in the LoRaWAN ecosystem

	Practices	***Expertise***	***Implementations examples***
Network provisioning	Network deployment, operation and maintenance	RF and networking, field testing, equipment commissioning, security	Connectivity-as-a-service (service provision) Private networks Crowdsourced public networks
Hardware development	Product design, Hardware manufacturing, Certification, Assemblage of components	Hardware engineering, wireless and networking, embedded systems, mechanical and electrical engineering, Industrial design	Custom hardware Bricolage hardware (for small-scale deployments) 'Unfinished' (own use)
Application development	Data processing and integration with cloud services Interfacing with end-users	Computer science, software development, Big Data management, privacy and compliance	Air pollution monitoring Asset tracking and monitoring, End-node visualisation and mapping
System integration	Custom solution implementation, Institutional liaising	Modelling, Analytics/AI/ML, Business domain expertise	Cold-chain management Smart agriculture (Livestock tracking, crop monitoring) Smart city

As mentioned earlier, beyond the realm of TTN, it is crucial to recognise the role of actors fulfilling complementary activities such as vendors and IoT platform providers. Although they too contribute to innovation and produce inputs for specific implementation arenas, at this stage, I consider them only tangentially for the sake of analysis. Figure 17 depicts the sociotechnical value chain within TTN, which includes the multiple linkages within and across the boundaries of the four implementation arenas. These linkages are sustained through the joint collaboration around key boundary objects (e.g. architectural diagrams), standardised interfaces such as GUIs, APIs and authentication protocols, and cognitive interfaces such as conferences and technical workshops. In the diagram, vendors are depicted as external suppliers of stable technological offerings -e.g. routing services, middleware, sensors, modules or network components. However, other vendors and intermediaries, not included in the map, may also be involved in the production of IoT solutions. For example, design consultants or development software vendors. In the following subsections, I describe each of the four implementation arenas.

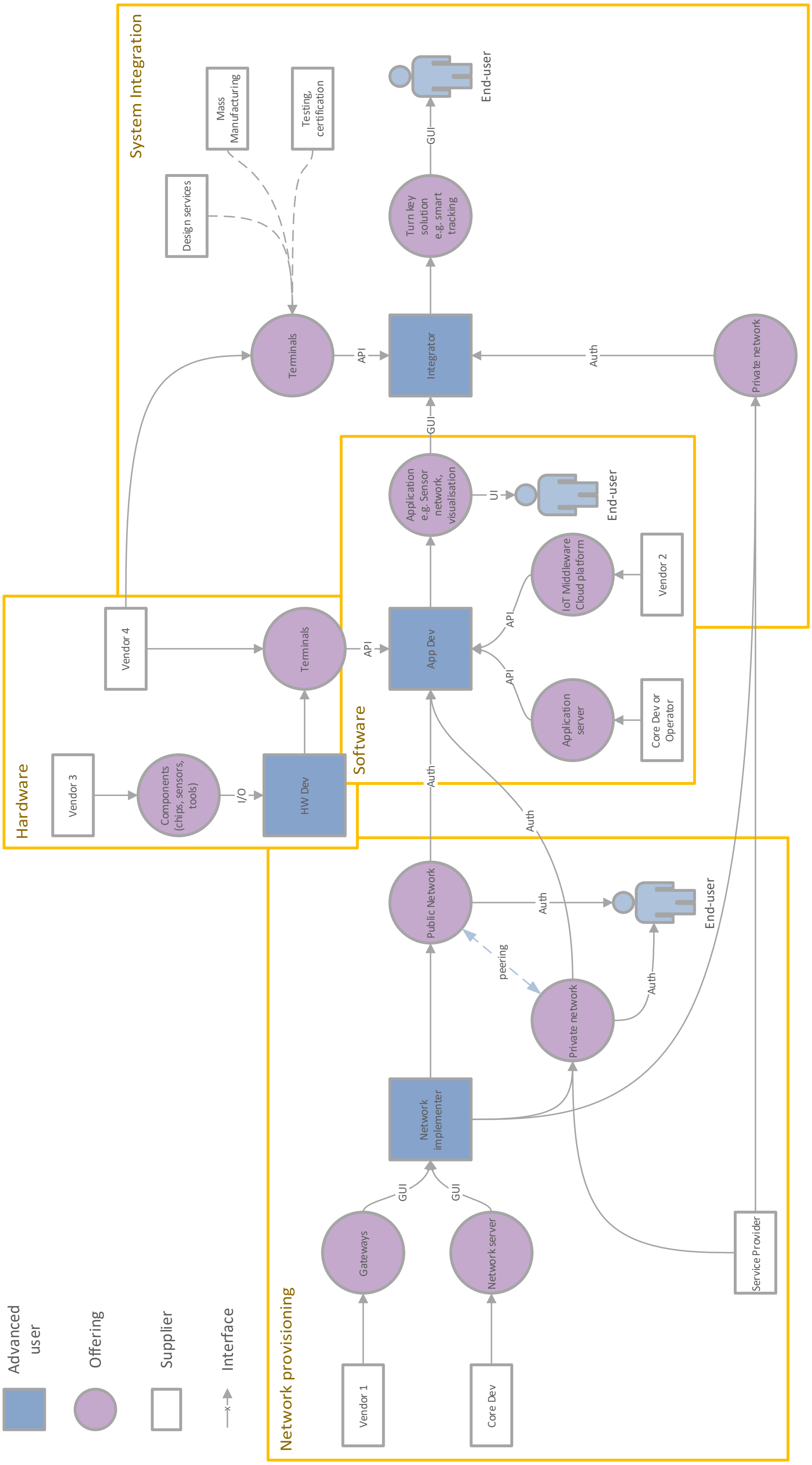

Figure 17: Sociotechnical value chain and implementation arenas in the TTN ecosystem

Network provisioning

This arena entails the initiation, maintenance and scaling up of the local data networks. As I discussed earlier, modularity, the low costs of components and network access, and the availability of open-source network software are some of the factors affording dispersed actors to engage in the provision of networks. In the LoRaWAN ecosystem, network software suppliers such as The Things Network, enable dispersed actors to control local network deployments autonomously. In practice, this practice involves adapting and configuring network servers, commissioning gateways in strategic positions, giving secure access to users and monitoring the performance of the network.

The focus in this arena is on delivering LoRaWAN connectivity as the primary technological offering, which is made available to a range of advanced users. Network implementers may carry out this activity either for their own use (e.g. for experimentation, learning and research or private projects) or to deliver services to other secondary users such as application developers, system integrators or induvial and organisational end-users. Connectivity may be offered through different deployment scenarios, for example, as a public service, with no quality guarantees, or privately, where minimum assurances and service level agreements (SLA) may be put in place. In this sense, network implementers may also operate as network service providers commodifying network access directly to end-users. As described in chapter 6, certain network elements have been strategically decentralised and are operated by regional brokers working in partnership with TTN. Finally, in the case of private networks, connectivity may be leveraged for other third parties or users external to the private domain through the use of traffic peering agreements that allow the balance of load between neighbouring networks.

Hardware development

> There is a lot of product development in the community. Groups best positioned are traditionally existing product designers; LoRaWAN is typically just a new module for them, but RF specialists are of great value to get the most of out of the characteristics of LoRa Interview with Johan Stokking (June 2019)

The second arena concerns the production of physical devices or ‘things’. The development of new IoT terminals is carried out by professional hardware developers, non-professionals or academic researchers. This activity entails the design and assemblage of devices through the use of tools and building blocks such as development boards, modules, sensors and development software. The different elements of IoT artefacts are coupled together via standardised interfaces (e.g. I/O pins and APIs) and programmed via software, allowing different degrees of complexity and scaling up. The development of hardware is often targeted to the sphere hardware vendors or makers and often touted as low threshold activity alluding to the low costs of components. Core-developers pursued the development of gateways at the very start of the initiative in order to underpin the idea that low-cost hardware will facilitate de uptake of the technology. However, the scaling up of hardware devices demands the availability of resources and coordination with a range of suppliers and intermediaries. At medium and large scale, hardware development involves economies of scale and a complex supply chain of hardware design, software, manufacturing and certification. As a result, specialisation also occurs within this arena as certain stages of the process get outsourced, for example, to design firms and contract manufacturers.

This arena is inhabited mostly by exiting hardware vendors in the industry and by emerging players serving different markets. At the time of writing Semtech (2019) reported on its website a list of 451 products including end-nodes, gateways, modules and starter and testing kits, of which 288 are end-nodes targeted at a diversity of ‘verticals’ (i.e. agriculture, cities, environment, home and buildings, industrial, metering, healthcare and supply chain and logistics) as well as 20 design partners offering expert services for product development. This is, however, an early stage for vendors competing in an emerging market of generic and custom hardware.

Figure 18: commercial LoRaWAN hardware (photo from TTN conference January 2019)

Albeit at a smaller scale, hardware developers and non-professional groups also partake in the production of devices oriented for specific projects. Experienced developers, researchers and non-experts are among the groups engaging in some form of bricolage and custom hardware design. As a hardware developer pointed out in an interview:

> There's no point in us making a temperature sensor because that's low hanging fruit and everybody has done it, and so you can just buy them off the shelf for less than the cost it would be for us to make them [...] But there are still higher value unusual sensors, and we've been making things that bridge from ZigBee to LoRaWAN for use in explosive atmospheres, which is a very niche kind of industrial application for oil and gas industry and that's interesting, and there's more value in it for us. (Interview with hardware developer, May 2019)

Similarly, citizen science initiatives are an example of non-commercial hardware production efforts. In this case, microcontrollers fitted with sensors and sturdy enclosures have been deployed in the open to capture data from the environment. This type of initiatives may provide online detailed instructions and blueprints to enable volunteers to build the sensors themselves. Such initiatives either remain small scale and managed through alternative models such as crowdsourcing and volunteering. Figure 19 shows an air pollution sensor built with programmable microcontrollers and off-the-shelf components designed by Luftdaten, a citizen science initiative crowdsourcing environmental monitoring in Europe.

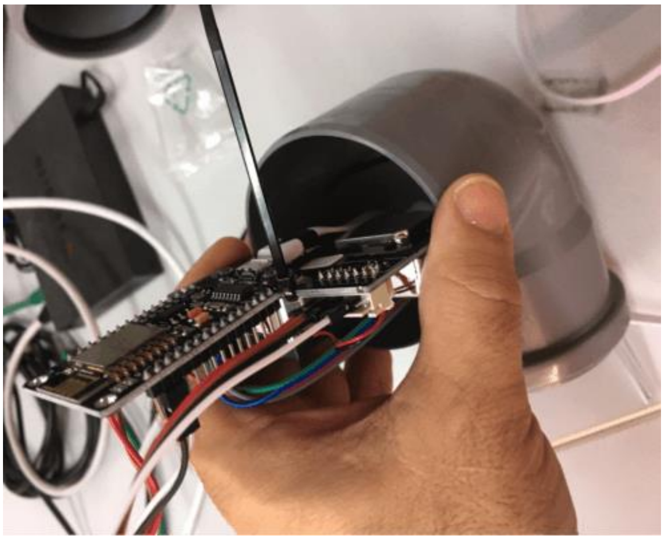

Figure 19: DIY air pollution sensor (Luftdaten, 2019)

Application development

This arena comprises the leveraging of sensing infrastructures by turning the data captured by sensors into valuable information. Application development may involve a different set of skills than hardware development altogether. At the level of application, the task is to integrate the flow of data into relevant uses with the help of processing, analysis and rendering tools like visualisation. While the focus of hardware development is on electronics and low-level programming, the expertise of application developers revolves around computer science, high-level programming and data management. Application developers are not obliged to be in proximity or have knowledge about the inner workings of hardware. While developers with direct access to terminals could well engage with hardware directly, this is not a requirement for application developers. Developers may access devices and their data remotely via authentication protocols or rely on modelling and simulation.

In this arena, complementary suppliers such as cloud service providers and IoT platforms (also known as middleware) interact with developers with data management and advanced computing services through the use of APIs. The role of these actors is to reduce the complexity in the development process by leveraging economies of scale to offer computing facilities, device management and visualisation tools. Resourcing to third parties demands a degree of trust from developers to ensure data integrity and security are not compromised. As a result, the range of third-party services is not limited to cloud services but also accommodates so-called ‘on-premises’ deployments, where processing systems remain within the boundaries of the users’ facilities. The exigencies of applications and their specific context have implications for the way networks are dimensioned and scaled up. An application for smart agriculture in rural areas would, for instance, comprise an entirely different deployment in terms of data collection and analysis than a smart city application.

In the case of commercial applications, professional developers may engage with the development of applications either as members of technology organisations or as entrepreneurs. However, analogously with hardware, not all applications are developed with the goal of commercial mass adoption as exemplified by non-profits or citizen-science initiatives which have also adopted LoRaWAN for its technical fit with environmental monitoring. Figure 20 shows the user interface of Luftdaten’s network of air pollution monitoring where data from sensors is aggregated and plotted in a map to convey information to users and stakeholders. In this example, developers leverage connectivity and hardware to produce a value-added public service through parsing, analysing and visually rendering the data from sensors in the ground.

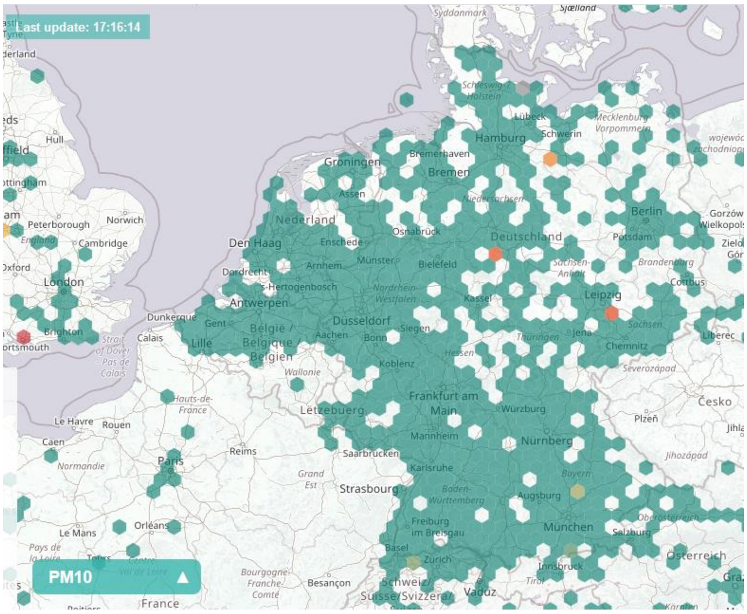

Figure 20: User interface of the Luftdaten network showing the map of aggregated air pollution levels (Luftdaten, 2019)

System integration

System integrators (SIs) take up the task of bringing together different components (e.g. hardware, software, networking) into coherent working systems. The goal of SIs is to deliver full-fledged solutions to contracting organisations by dealing with the complexities of connecting, interfacing, translating and customising a range of different underlying elements. Institutions with no internal technical capacities, such as a city council, might outsource the delivery of so-called end-to-end or 'turnkey' solutions to SIs. Integrators, in this sense, operate by establishing ongoing interaction with the suppliers of components. Implementing a complete solution may thus require direct involvement in one or more of the aforementioned implementation arenas. Alternatively, system integrators may themselves engage with network provisioning, hardware development, and application development. Integration with other instances of data processing and management such as ERP systems and combination with other sources of data is also an essential part of leveraging outcomes from other arenas. In the words of a TTN system integrator:

> Information might be useful in dashboard and it might be useful to general alert, in lot of instances that information will be more valuable if it can be then passed on to other systems of records and others applications that would benefit from utilising it in a different matter. For instance, in smart building, if you put environment sensors that monitor the temperature and the humidity, as we do routinely with our clients, the first use for people its going to be maybe an app that will allows them to very quickly know what's going on, but that same information could be feeding existing systems they have such as a building management system with suddenly gives them more rich information to be able to control the heating and ventilation system. (Paumelle, 2019)

Conjointly, system integrators maintain continuous institutional liaising with clients outsourcing the provisioning of smart solutions (e.g. city councils, real estate or transport agencies). The expertise of system integrators is therefore focused strongly on the demand side. Adequate business domain (or vertical) expertise allows integrators to formulate relevant solutions and establish long-term relationships with contracting organisations or end-users.

The focus on integrators has progressively become a priority in the discourse of innovation in TTN. An online getting-started guide by TTN, called 'become an integrator' (The Things Network, 2019a), for instance, lists a set of steps to aid developers innovate and pursue the development of business cases for IoT solutions. The guide warns of the risk involved in entering the IoT market and includes a series of milestones: exploration, proof of concept, scaling and production. This representation is a good illustration of the broad spectrum of practices that span across the different innovation arenas and at the same time makes explicit the hurdles developers may face in the pursuit of bringing IoT solutions to the market.

Enchained cycles of learning: A framework for innovation

I have thus far dealt with innovation as a cross-cutting theme in distributed infrastructures. That is, as pertaining to the production of new products, services and solutions, as much as to the improvement of infrastructural components. The metaphor of arenas of implementation and development as construed here offers a useful way to illustrate the division of labour that takes place when different expert users link up their skills and practices to produce coherent applications and solutions. Each arena constitutes, in essence, a space for social learning where knowledge is produced locally but also shared through different means with other arenas. This schematisation also flags the need to acknowledge the uneven degrees of involvement of different expert users who, depending on their expertise, may take up various active roles in the value chain such as network implementers or application developers. In turn, the technological offerings produced by certain advanced users may also be deliberately unfinished and aimed at other expert users (or developers).

A helpful way to capture this expanded notion of innovation is to look at how cycles of learning take place *within* and *across* different implementation arenas (Figure 21). The knowledge that is accrued throughout processes of infrastructure deployment informs not only the development of new applications but also very practical decisions aimed at growing and maintaining infrastructures. Knowledge about users and their practices is critical for innovation and might be captured through different feedback mechanisms which allow for productive exchanges within and between different arenas. In this way, patterns identified in different arenas of implementation may be incorporated into the conception of iterations of underlying infrastructure components. In this model of innovation, the growth and improvement of distributed infrastructures and the development of applications that they supports are mutually reinforcing processes.

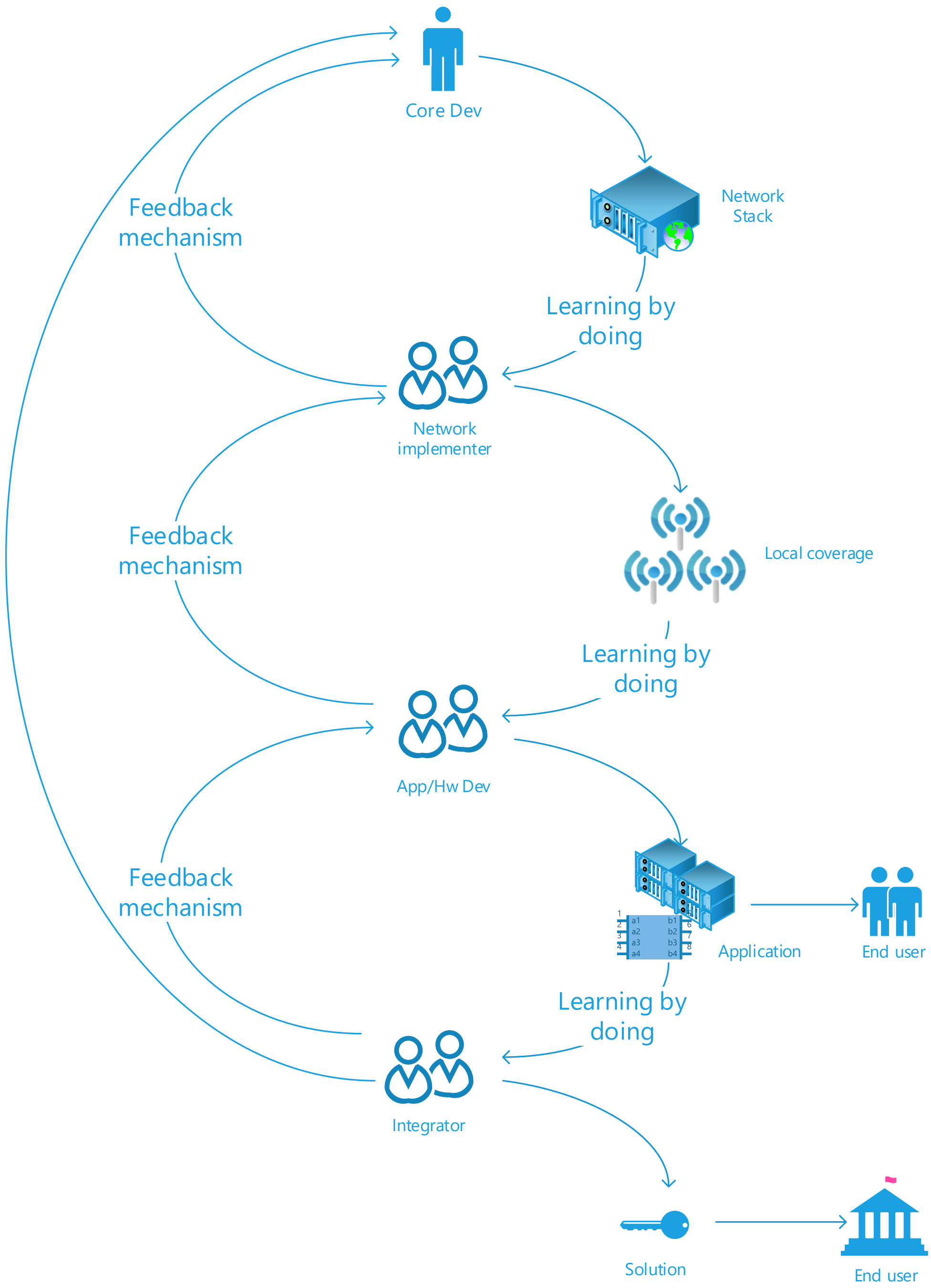

Figure 21: Cycles of learning between implementation and development arenas

An early instance of learning can be observed in the development of the network architecture. While early prototypes may mostly rely on self-referential user representations, over time, technical work benefits from knowledge about the ongoing efforts of implementing infrastructure and developing products, services and solutions. Once the installed base is in place, contributors leverage its capabilities through applications built with modular buildings blocks which in turn may lead to the growth of the infrastructure or trigger upstream changes in the design of the architecture in the long run. As the case of TTN show, this is a process of diminishing returns. While minor incremental changes in the architecture are generally implemented at a high pace, major upgrades take increasingly longer development times as the network design stabilises. Looking at the development of software, for instance, earlier versions of the backend (V1 and V2) incorporated more inputs from users[33]. With a stable network in place, more effort is then invested on the ground in scaling up the network, implementing use cases and establishing strategic alliances. In response to my inquiry about the process of validation, Johan Stokking replied: 'we figured out the role of our infrastructure and technology; validation is less important than in the beginning. Still, with the release of V3 coming to the public, we expect a lot of feedback and we're designing ways to gather that in a good way back to the product team' (Stokking, 2019).

As an outcome of learning processes, certain technical features or key choices are preferred over others or finetuned accordingly, which have implications for actors engaging variously across the value chain. These decisions are operationalised not only materially through design, but also organisationally and in strategic decisions. Some influential factors, for instance, include the degrees of malleability that are inscribed into artefacts, their accessibility in terms of cost and the availability of knowledge to configure them. A preference for modularity is a crucial aspect insofar as it affords a decoupling of technical constituents but also of practices. By making the network architecture modular and decentralised, components can be installed and scaled up as needed by different types of advanced users. Similar cycles of learning by doing, learning by implementing and learning by using occur within other arenas. Due to the costs involved with implementing local coverage, use cases and prototypes are tested

[33] A good measure of the amount of changes incorporated in the network backend is can be obtained by observing the publicly available log of online activity by core developers. According to the metrics obtained from GitHub, in the period from the launch of V3 in April 2019 until June 2019 there have been around 380 pull requests submitted almost at a daily rate (see The Things Network, 2019d)

before committing to scaling up. Coordination mechanisms are critical for planning purposes and for ensuring the networks are well-dimensioned to run applications.

Conclusion

In this chapter, I have scrutinised the various forms of involvement in the production of applications, services and solutions that are supported by distributed data networks. I have shown that innovation in this context needs to be understood as a cross-cutting theme where different forms of infrastructure work are deeply interdependent. As a starting point, I have laid out a genealogy of users by looking at the active roles that have been bestowed on them within the purview of decentralised data-networks. With these considerations in mind, I have proposed to assess the uneven contributions of users by tracing the mechanisms of mutual learning between the range of actors. I have argued that the outcomes of such mutual learning processes are operationalised by different means of coordination and design strategies. By looking at the embodiment of those design strategies, the division of labour starts to emerge where core developers have purposely delegated innovation activities. Informed by long processes of learning, developers have privileged certain designs over others in the pursuit of decentralisation, scaling up, low manufacturing costs.

The TTN ecosystem subsumes a highly diverse and heterogenous range of contributors with technical and domain-specific expertise. Not only do different actors have different motivations, but also, they contribute with their own set of skills and business acumen. The technological offerings of some actors thus become the resources for others who add value through standardised interfacing and conventions in a complementary and synergetic fashion. In order to capture such complementarities, I have sketched a map of the value chain in the TTN ecosystem, drawing the contours of arenas of development and implementation.

The case of TTN shows that innovation takes place not only in the process of infrastructuring but also on top of the emerging infrastructures. On the one hand, novel architectures and modes of organising work are devised and probed by developers and refined during deployments owing to ongoing learning mechanisms. On the other hand, the emerging data networks afford experts and non-experts the possibility of building new services, applications, use cases, products, and solutions with varying degrees of scope and scale. Ultimately, both manifestations of innovation are mutually reinforcing insofar as their rewards may stem from positive network externalities. This effect falls in line with previous empirical studies of information infrastructures. Hanseth and Braa (2001), for instance, suggested that a 'learning reinforcing mechanism' takes place within information infrastructures whereby the more services are supported by the infrastructure, the more attractive it is to new users. Users, in turn, generate new knowledge and possible uses, which can be employed to change infrastructure components such as the architecture.

There is a need for broadening the understanding of innovation beyond the locales of conventional market-based relationships in order to recognise instances that seem to escape the rationale of commodification. The case of TTN offers two concrete examples: the implementation of 'best effort' public networks which remain functional despite the absence of financial incentives; and the deployment of bespoke applications for the crowdsourced acquisition of data for public benefit. The diverse configurations of specialisation and complementarities in an ecosystem suggest novel ways in which disparate actors strive for sustainability and business propositions. Moreover, the growing interest in the value of data brings to the fore pressing questions about data control and ownership, privacy and security. In this sense, controlling the infrastructure and the means of data collection constitutes a strong incentive for the adoption of decentralised infrastructures. As nicely put by Michel Callon (2004, p. 8):

> Designing an innovation or a technology means participating in the shaping of new agencies or in the reconfiguration of existing ones; it doesn't mean only responding to demands or to satisfy needs. Debates on agencies, and consequently on forms of arrangements and on the innovations that we want, are under developed. For example, we consider that economic agents are homo economicus and we format markets so that only this type of economic agency prospers. But there are thousands of other ways of being economically rational. We must be aware that when designing ICTs what is at stake is the type of human agency, of human being we want to develop.

Chapter 8 – Discussion, contributions and final remarks

Introduction

This study unfolds in the wake of emerging wireless communication standards under the banner of low-power networks (LPWANs). These standards are competing in a specific segment in the IoT industry-oriented primarily to connected sensors. In this landscape, I have focused on an initiative to build a global IoT data network which places decentralisation and various forms of collaboration at its core. This unusual approach departs from the modus operandi in the industry, and the prevalent top-down model applied in the construction of information systems and telecommunications infrastructure. The proposal for this study was not only to scrutinise the peculiarities of the model but to arrive at a detailed map of the terrain as an alternative to the dominant macro-level perspective of the IoT policy and industry discourse. In doing so, I have delineated the boundaries of an emerging ecosystem and examined its members' everyday efforts to reckon with and realise a challenging infrastructure project throughout its early years of existence. Building on an interpretivist epistemology and an ethnographic methodology, I have followed the work carried out by a coordinating group and a range of contributing actors around the world. Throughout this enquiry, I aimed to establish nexuses between the discursive representations of the future and the struggles to accomplish them; the bird's eye view of statistics and the immediacy of participant observation; the short and the long term; and the local and global dimensions of infrastructure.

In this final chapter, I bring together the findings of the study. I begin by revisiting the research questions and assessing to what extent they have been addressed. I then discuss the broader salience of the findings of this thesis in light of a changing sociotechnical landscape in the IoT industry highlighting the exceptionality of TTN model as well as identifying some commonalities with emerging data-oriented business models. Next, I outline the main theoretical, practical and methodological contributions of this thesis in connection with the literature. First, I argue for the need to extend the framework of 'information infrastructures' in the purview of decentralisation, distributed forms of infrastructuring and data networks. Second, I suggest that existing theories of 'user innovation' need to be revised to account for the multifold contributions of users and other actors in settings of collaborative technology production. I propose that a nuanced assessment of the role of non-conventional actors is crucial to inform practitioners and policymakers. Third, I summarise some of the specific techniques developed for accessing multiple sites which may prove helpful for other STS research projects and more generally for the development of multi-sited ethnography as a method of enquiry. I end by flagging the limitations of this study and proposing future avenues of research.

Research questions revisited

Looking back at the research design proposed in Chapter 4, I set out to answer four research questions which have been tackled across three chapters of findings (5 to 7). I have sought to address these questions constructively building on my empirical work and a theory-informed analytical framework. However, this is an enquiry of an ongoing phenomenon and, therefore, the findings of this study are not intended to offer definitive conclusions to the research questions. Indeed, the process of answering the questions has necessarily prompted further empirical and theoretical work. In this section, I discuss how each of the research questions has been answered and what issues remain open.

> RQ1: What are the types of technical work, social organisations and technological offerings produced within TTN ecosystem?

This question called for identification and classification of the diversity of work practices performed by actors in the ecosystem as well as a taxonomy of the universe of dispersed actors and the array of artefacts and other technical constituents of data networks. By recounting the trajectory of the initiative (in Chapter 5), I unpacked the rationale underpinning the initiative and the struggles to realise the ambitions of its creators. From the outset, the project of developing a decentralised network architecture was been envisaged to profit from the contributions of external actors and in that sense, the initiative engaged with multiple fronts. Based on my observations and interaction with a range of informants as well as on qualitative secondary sources, the preliminary taxonomy of actors evidences a confluence of various types of actors and social formations in the ecosystem. A good way to map this terrain is by taking the vantage point of the coordinating group from which it is possible to identify a universe of geographically dispersed (or peripheral) actors and a range of commitments and long-term visions. At the time of this enquiry, four broad types of social organisation became salient, namely incipient groups, formalised communities, private ventures and research initiatives.

By necessity, this is a provisional taxonomy insofar as the universe of contributors in the initiative is continuously evolving with new actors joining and some communities disappearing or being reorganised. While Chapter 5 provides a comprehensive overview of the initiative at the time of my involvement, the answer to this research question is subject to the particular timeframe and the changing conditions of the field. Indeed, local formations are in continuous transformation, with members regularly leaving and being enlisted and with changing organisational structures. The recognition of new social formations and practices (mainly from the Global South) which were almost absent at the outset of this study, signals a promising path for further investigation of this case. The types of assemblages are however indicative of the range of different levels of commitments and approaches which are subsumed in the initiative. The challenges of constructing decentralised data networks have given way to creative forms of governance and ownership, which are still being reassessed and reworked.

> RQ2: What are the factors influencing the decisions to initiate and operate local TTN networks, and what are the mechanisms for aligning and coordinating work between geographically dispersed actors?
>
> RQ3: To what extent are coordinators able to steer the scaling-up and trajectory of the TTN initiative at local, regional and global levels, and what are the specific strategic decisions aimed at succeeding in this endeavour?

One of the most salient findings of this study is that while the TTN initiative encompasses a vast diversity of (often conflicting) motivations and agendas, they seem to coalesce in a common space of interaction. As it became salient when looking into how disparate interests align, the goal of realising a global data network is confronted with a set of tensions and dilemmas. These two research questions called for an analysis of what controlling, managing and coordinating a large-scale network entail. To tackle them, I began the analysis in Chapter 6 by proposing to view the internet of things as (data) infrastructure and problematising the tension between long-term stability on the one hand and flexibility on the other. The Things Network initiative finds itself amid an ongoing battleground of IoT low-power standards. In this context, the project coordinators have envisioned and adapted their strategies of growth and managed lock-in effects in light of the diversity of interests. One can identify different facets of heterogeneity in the ecosystem: in terms of visions of growth, individual preferences and motivations, and forms of social organisation. This variability manifests in the multiple tactics used for untangling deadlocks and growing local networks and uncovered some of the pitfalls faced by peripheral actors. The struggles of initiating local networks evidence that growth in the context of decentralised networks is contingent on how local actors grapple with bootstrapping and scaling up at the locally relevant problem. In other words, the global dimension of the network emerges only as a result of the everyday work carried out at the local level.

The fact that local agendas are highly diverse is illustrative of how actors at the centre and the periphery imagine temporalities and scales. To be sure, long-term visions, modes of work and resource allocation of TTN coordinators differ from those of local actors. From the point of view of the project coordinators, finding compromises and resolving ongoing tensions appears as a highly difficult, and sometimes unworkable, task. Thus, rather than entailing an effort of management or coordination carried out by a single party, the successful instantiation of the decentralised global data network is by and large a collective achievement and the result of constant negotiations (between commercial and non-commercial interests, short and long-term goals, local needs and global growth expectations). I have sought to capture such a process with the notion of distributed infrastructuring. In this sense, the project owners can only *orchestrate* their visions of growth through the use of a range of design choices, liaising mechanisms and strategic alliances. In light of the impossibility of aligning disparate interests, the notion of orchestration suggests that a constant reassessment of tactics is needed to enable autonomy to contributors and maintain a stable interoperable network.

To give a definite answer to these questions, it is however necessary to assess whether TTN has been successful in its promise. While in the 4-year timeframe of this enquiry the initiative has seen remarkable progress in reaching a large number of contributors and a substantial installed base, tensions are still unresolved, and it remains unclear whether it will succeed in the long-term. Whether the proposition of TTN will find a sustainable model remains a matter of future enquiry. The issue of sustainability flags the need to deal theoretically and empirically with the long-term of infrastructures: it prompts a further assessment of what success means in the context of a non-profit data infrastructure project and whether either strategies or expectations will need to be reworked to ensure its survival.

> RQ4: How do dispersed forms of work lead to the production of innovations and durable networks?

The myriad applications found in the TTN ecosystem show that IoT data networks are not built for their own sake without regard to the kinds of services they can support. Instead, the specific applications that rely on low-power networks seem directly to inform their design, roll out and scaling-up. And conversely, the process of developing IoT applications and solutions is framed by the affordances and constraints surrounding low-power networks. These interrelation prompts for an assessment of innovation as a crosscutting theme which pertains both to the architectural improvement of networks and to the production of new products and services.

The changing discourse of the project owners in regard to innovation and sustainability suggests that the development of application and solutions and the long-term stability of networks are deeply interdependent aims. Over time, the focus of core-developers has gradually emphasised the need to develop business cases. This issue is salient in the way TTN coordinators have adapted their user representations from addressing external contributors as the initiators of local networks, to casting them as developers and integrators of solutions. This shift is not sudden realisation or a change of plans: refining the technical, discursive and organisational constituents of the initiative, has rather been a long process of mutual learning between the actors in the ecosystem.

The case of TTN, calls attention to the need to substantiate the often-loose invocation of the term ‘users’ by managers and practitioners as well as theories of ‘user innovation’ and ‘user-centred design’. It is thus necessary to unpack the positionality and agency of users, investigate their specific contributions in settings of collaborative development and ultimately map out the division of labour in the value chain of low-power IoT. In the TTN ecosystem, innovation entails the successful coupling of complementary practices such as the provisioning of networks, the development of hardware and software and the integration of these elements into coherent solutions. Such coupling is facilitated by mechanisms of learning, boundary objects and the use of adequate interfacing. In this context, innovation can be described as a series of overlapping cycles of learning between arenas of implementation and development focusing on technical activities such as networking, hardware development and applications development, as well as on domain-specific work surrounding the integration of IoT solutions.

Discussion: Locating the broader salience of the study

The boundaries of collective innovation in the internet of things

The idea that technological development could profit from the active involvement of users is not a new one, particularly in the realm of ICTs. Since the advent of computers and the internet, this phenomenon has been explored from various disciplinary perspectives, including management studies, critical theory, participatory design, HCI information systems research, and STS. As I have outlined in Chapter 2, the most salient theories and models from the literature frame the phenomenon in terms of democratisation, shifting configurations of labour, diversity in participation, user-centredness and emerging forms of organisation. More broadly, feminist scholars have shed light on the gendered nature of technology and flagged the need to problematise the relationship between users and technology. These views have been influential in science and technology studies where technology and society have been theorised as deeply entangled and 'co-producing' one another.

In STS, the role of users as critical agents in technology development has been a central issue in the research agenda for the last three decades. While a great deal of conceptual progress has been made since the 'turn to the user' in STS (van den Scott, Sanders and Puddephatt, 2016; Hyysalo, Jensen and Oudshoorn, 2016), new socio-technical configurations demand asking new conceptual questions and revisiting the prevailing category of 'the user'. There is now a need to assess whether and how existing understandings of user involvement in innovation have caught up with recent technoscientific developments such as the rise of data-oriented infrastructures. A step towards bridging this gap entails unearthing the uneven contributions of those actors located outside the typical loci of technology development in the context of emerging data-oriented sociotechnical formations.

The salience of this study is for the prospect of the internet expanding not only in scale but in scope, becoming increasingly pervasive and enabling the mass collection of data. The vision of ubiquitous internet connectivity and connected physical objects has been heralded by industry analysts now for more than two decades, with a wide-ranging set of uses and services that exploit the increasing availability of data for purposes of surveillance, automation and prediction. The distinctive challenge of the IoT lies in its vague definition, the seeming convergence of multiple technological domains and its vast potential for applications. This trend is largely predicated on numbers (of devices, of users, of traffic, of investments), which gives us but a macro view of technological trajectories and optimistic extrapolations into the future. A bottom-up micro-level exploration thus emerges as an adequate response to investigate unconventional modes of user involvement in the construction of IoT data networks.

Distributed and community-led approaches to technology development have seen varying degrees of success in the areas of software, hardware and internet infrastructure. Three noteworthy examples which are still relevant today are wireless community networks, free and open source software and open hardware. Existing communities and practices associated with these forms of bottom-up collaboration seem to have found a commonplace in the world of connected objects. To be sure, there is a continuity of existing agendas and principles which are now being translated to processes of massive digitisation. Previous empirical studies of open source and community-led initiatives have pointed to different factors that explain the involvement of users such as political activism, the need to bridge functional gaps, economic efficiency or sheer pleasure in the practices of repair, tinkering or hacking. These past ecologies are still latent and strongly influence the practices and tactics applied in the sites of enquiry of this study. The Things Network ecosystem is in fact inhabited by various members of community wireless networks and hackerspaces and relies, at its core, on the practices and principles of open source software. To a great extent, the findings of this study show that the motivations of the members of TTN fall into the same categories of previous bottom-up efforts. Yet, the newly-found value of data as a commodity and the need to integrate hardware, software and network connectivity, brings about new challenges and raises new questions in regard to the advantages and feasibility of decentralisation and unconventional modes of data ownership and control.

The project owners, who are well acquainted with entrepreneurial and business practices in the technology sector, draw strongly on the arsenal of theories, models and methods of open and collaborative innovation found in the management literature. By and large, putting methods into practice, writing guidelines and articulating co-creation strategies entail political decisions as to who is considered to be part of the innovation collective, and who is not. At first glance, a strong democratising ethos seemed central to the vision of TTN. While the allusion to radical forms of participation has been attenuated over the years, this was more salient from their original motto: ‘a global, crowdsourced, open, free and decentralized internet of things network’ (Griezman, 2015). The slogan of ‘building together’ was similarly a call for anyone with the knowledge and means to take on complex technical work to join the collective. This however represents a very narrow group of players in the universe of IoT actors, and in fact, the path to sustainability seems increasingly to rely on the feasibility of business cases and the availability of resources. These caveats call for a cautious assessment of the how the terms ‘democratic’, ‘open’ and ‘bottom-up’ are often conjured up amid technology circles. Indeed, as in the case of open source, previously radical ideas about democratic innovation have been mainstreamed into business practice and repurposed to accommodate not only an agenda of openness but an efficiency-oriented organisation of work.

Dealing with ambivalences: A hybrid model and strategic clustering of duties

At the outset, a business model was not a priority for the founders of TTN, and hence the initiative was predicated as a non-profit foundation and underpinned by a short manifesto. Rather than a business plan, this document constituted an instrument for reaching early agreements and establish an underlying set of principles. A public network backend was offered free of charge while the cost of deploying and maintaining the physical elements of networks was taken care of by users. Developers and implementers wrestled at the early stages with 'tragedy-of-the-commons' type of dilemmas such as how to enable openness while avoiding free-riding; or how to encourage the fair use of 'free' resources. Similarly, technical challenges concerning quality of service, resilience and scalability were dealt with on a case-by-case basis by local groups, while core-developers sought to develop global-scale solutions. Different solutions and models of governance at both local and global scales have been proposed and tried out including strategic alliances and alternative organisational structures such as cooperatives and membership-based schemes.

Going past the initial excitement about the prospect of openness and decentralisation, one of the most pressing issues faced by backers of the initiative throughout its early years was the need to find a unified and sustainable scaling-up model. Despite the dropping costs of hardware and the open-sourcing of code, the construction of internet of things infrastructure remains a highly complex and strenuous activity. Deploying coverage demands plenty of resources and effort, which in the case of decentralised networks cannot be planned and managed following the conventional approaches used by large operators for demand forecasting and modelling. Even though experimental networks and use cases are critical during the bootstrapping stage, these are usually kept to a minimum or maintained under the rubric of 'testbeds'. A recent example in the UK is the partnership between the innovation agency Digital Catapult and TTN in an effort to provide a testbed to stimulate innovation (Digital Catapult, 2018). The expansion of local networks seems to be mostly driven by specific projects, solutions or 'business cases'. This approach to scaling up demonstrates the extent to which infrastructuring and the development of applications are highly intertwined and interdependent endeavours.

As suggested in chapter 7, the generation of applications, solutions or business cases, as well as the refinement of underlying network components, can be explained as a series of enchained cycles of mutual learning between core-developers and different groups of expert users. In TTN, four complementary spheres of action coalesce in the production of functional IoT applications and solutions. These are network provisioning, hardware development, applications development and systems integration. Actors in each of these spheres partake in the value chain through sharing knowledge and coupling their work via interfaces such as APIs, authentication protocols, graphic user interfaces, documentation and other liaising mechanisms. Technical and cognitive interfaces, as well as representations and depictions of plans and architectures, are vital in allowing interoperability and translation between different deployments and third-party systems. At the same time, these resources are used to enable and constrain actions between separate specialised groups.

The expertise-oriented division of labour of this ecosystem has enabled the production of new services and applications in different verticals, but also, over time, core-developers have produced crosscutting innovations mainly oriented to fostering integration and global scaling up. Examples of such infrastructural innovations include improvements to the network architecture, new modules and functions, end-to-end security protocols, new mechanisms for traffic exchange, geolocation, roaming and interoperability options between operators. Some of these innovations have a broader scope of action than the TTN ecosystem. For instance, by privileging interoperability between operators over lock-in mechanisms, the focus has been on generating positive network externalities such as the involvement of more players in the broader landscape of LoRaWAN.

Linked with the problem of scaling up is that of accommodating disparate agendas and bringing (sometimes conflicting) plans and roadmaps to fruition. Although there is no definite resolution to this issue, some progress has been made. Throughout the years, TTN concocted an array of commercial offerings that coexist with the ‘public good’ status of community networks. Professional services and resources with guaranteed quality of service are commercialised under the auspices of a private firm: The Things Industries (TTI). This business model is not new to the market and indeed competes with other commercial operators. In this way, TTN has morphed from its original democratising guise into a middle ground between a community-oriented ethos and a coherent offering promoted by its commercial counterpart. This ambivalence, albeit subject to unfair distributions of costs and benefits, has so far been tenable due to the effects of positive network externalities coming into play. In other words, a growing installed base and overall popularity of the standard brings about good leverage for the provision of complementary professional services. In this sense, the overall benefits seem to outweigh the concerns about over-utilisation and free riding.

While the hybrid model constitutes a mechanism to subsidise the operation of a global public network, it is not sufficient. At this point, I would like to backpedal to pick up on some of the technical pitfalls engendered by decentralisation. As I demonstrated in Chapter 7, the affordances of a modular architecture have been a means to distribute agency in the ecosystem. By design, the prime purpose of a decentralised public network has been to allow individuals, communities and institutions to own and operate network components autonomously as needed. Still, as it does not make economic sense for every node to run full-fledged networks locally, certain core elements will by necessity remain shared and centrally operated resources. The *public* status of the network requires that resources be used sparingly. Hence, this network is operated on a 'best effort' basis with no service guarantees and with limited technical support. Problems linked with latency, network availability and local traffic requirements eventually rise to the surface as demand aggregates. To remedy this problem, a clustering of functions has been established whereby major private initiatives located in different continents undertake operation tasks by decoupling and brokering key network components. National or regional operators based, for example, in the US, Brazil, Australia or India also offer public access to the network backend while advertising complementary professional services and support for private deployments in a fashion akin to TTN. The clustering of competencies and functions seems nonetheless to be counterposed to the ideal of full decentralisation as it implies a degree of centralisation and gatekeeping. Hence my preference of 'distributed' over 'decentralised' as a more fitting descriptor.

A hybrid (private/public) model, the modularisation of components and the strategic clustering of key functions are ways in which some of the dilemmas and tensions between control and flexibility; between commercial and non-commercial pursuits; and between the short and the long term have been (at least partially) resolved thus far. The focus on creating open facilities for developers, seems to depart, at least for now, from a platform-like model with closed boundaries and lock-in incentives. Still, whilst the TTN ecosystem has grown as part of a concerted effort with other players in the LoRaWAN sphere, business strategies may undergo further instances of reworking, considering the issues mentioned above are far from settled. Assessing the success of TTN and the sustainability of its model remains a matter of future enquiry.

Exceptionality or efficiency?

Throughout the thesis, I have sketched a picture of a rather fragmentary global infrastructure with a diversity of deployments and irregular patterns of growth which are not adequately captured by classic network economics. In contrast to infrastructures operating within a single application domain, TTN is a case where local networks are provisioned anew and dimensioned according to each particular deployment. The idea of bootstrapping is thus not only illustrative of the inception of the initiative at large but also of the challenge of validating and expanding infrastructure at the local level –a process I labelled 'second-order bootstrapping' (see Chapter 6). This process strongly resembles earlier events such as the birth of the Internet itself and emancipatory technology movements, and indeed, the project owners drew their inspiration from the organic and decentralised origins and promises frequently described in accounts of the internet (see Chapter 2).

The concept of distributed infrastructuring has been proposed here as an attempt to capture the ways in which heterogeneous and geographically dispersed groups carry out infrastructure building work in a piecemeal and autonomous fashion finding a meeting point with a common technological baseline. The Things Network initiative tells a story of how agency has been successfully distributed to a range of actors through the finetuning of features such as layering, modularity, flexibility and standardisation. These characteristics appear to be radical and exceptional in many respects compared to more conventional approaches to construct infrastructure which have been adopted by competing organisations in the realm of IoT. A frequent point of reference has been Sigfox, a French firm relying on a proprietary wireless communications protocol, venture capital and strategic alliances with operators to drive the global scale-up of their networks. Similarly, competing in the LPWAN market are incumbent operators that leverage their installed base to deliver subscription-based low-power connectivity.

Yet, despite its distinctive attributes, this mode of infrastructuring shares similarities with other emerging forms of organising complex layers of technical work. Indeed, TTN may be viewed as another instance of a trend towards leveraging software architectures in a way that enables a flexible appropriation by different (organisational) users. One might find interesting parallels with frameworks and business models such Service-Oriented Architecture (SoA), Software as a Service (SaaS), Infrastructure as a Service (IaaS) or Platform as a Service (PaaS) which entail the on-demand delivery of generic technical offerings (e.g. routing, data processing or storage) via simplified APIs. These business models are an industry response to the challenges of scaling up information technology while catering for an ever-growing diversity of applications and technical requirements in an efficient manner. 'As a service' offerings, while supported by different functions of control to those of TTN, also open up the value chain to advanced users and different deployment scenarios through the full-fledged modularisation of computing resources. Such an approach has in fact been identified as a suitable line of business at TTN: its for-profit sister organisation adopted SaaS to deliver value-added network services as part of an hybrid private/public business model.

The concept of distributed infrastructuring can be helpfully used to make sense of these new efficiencies as it captures how a diversity of advanced users –who may be otherwise identified in cognate tech circles as developers, tenants, implementers or system integrators– link up their competencies in order to produce seamless technological offerings. Tracing the socio-technical relationships behind the construction of functional distributed infrastructures has important implications for practitioners. In the pursuit of efficiency, for instance, a substantive set of innovative practices might deliberately be shifted to expert users who are able to manage their risk and engage autonomously with suppliers to carry out their work. Once again, this mode of infrastructuring renders scaling up as a duty that is fulfilled at the edges but enabled or *orchestrated* at the centre. While application developers and network implementers fulfil a range of value added and operation and maintenance duties, network architects and core developers ensure the availability and functionality of essential network services. This logic of growth foregrounds the *infrastructural* dimension of innovation insofar as 'core' suppliers continuously incorporate new network functions and make them available to their users in generic form through interfacing. This infrastructural innovations are intended to minimise the complexity of development and implementation activities carried out by external developers (expert users) and thereby improve the overall efficiency of deployments.

Contributions to knowledge

This thesis offers an STS-inflected account of an idiosyncratic data network initiative and a model of innovation that captures the way in which geographically dispersed specialised groups within an ecosystem coordinate their work. The analysis contributes to two broad strands of research, namely infrastructure studies and the innovation branch within STS. At the same time, this is the first study of The Things Network conducted with an STS perspective and, hence, I hope to add –beyond an academic readership—to the ongoing efforts of practitioners and policymakers to grapple with issues of governance and sustainability. In this section, I distil the theoretical and practical contributions of this thesis and reflect on what can be learned methodologically from my experience of fieldwork.

Extending the remit of information infrastructures

To deal analytically with the complex and multifarious character of the internet of things, I have taken an infrastructural perspective. Drawing on the set of characteristics by Star and Ruhleder (1996), I described the internet of things as embedded in existing technical structures, social arrangements and conventions; defined by its temporal and spatial boundaries; built through processes of learning; and potentially taken for granted and invisible to the eyes of casual observers. This approach entailed the unearthing of the work that remains hidden behind macro statistics and dominant industry discourses. Conjointly, this perspective is a call to consider the question of temporality seriously in both empirical and theoretical work.

In the analysis, I invoked the idiom of infrastructuring as a way to talk about the ongoing character of the everyday practices associated with the making of infrastructures. Infrastructuring constitutes a helpful heuristic to register the complexity of work that spans multiple actors, temporal stages and locales and has been applied in different domains and types of infrastructures such as information management systems, e-health, e-science and wireless networks (Karasti, 2004; Pipek and Wulf, 2009; Star and Bowker, 2010).

Much of the recent literature making use of the term draws on case studies of infrastructure projects, organisations and communities of practice wherein unforeseen challenges and tensions call for design interventions. One might look, for example, at the recent work within participatory design and CSCW where different 'modes' of infrastructuring have been mobilised to enable the participation of more actors and democratise innovation (Karasti and Baker, 2008; Björgvinsson, Ehn and Hillgren, 2010; Le Dantec and DiSalvo, 2013). Within the boundaries of a project or single organisation, problems are often schematised in terms of *horizontal* coordination between different groups, typically between designers and users of a particular system. A nice illustration is the concept of community design (CD) as formulated by Karasti and Baker (2008): 'CD is a radical form of design because "empowered" community members have taken design and decision making into their own hands. It can be seen as shifting the (non-member) professional IS designers' taken-for-granted responsibility for design decisions and innovation to community members.'

This thesis, however, goes beyond the framing of infrastructures within a single project or organisation. In the case of TTN, various disparate motivations (or so-called verticals) are confronted with the prospect of a global vision which complicates the efforts of coordination to build shared or private infrastructures. This issue is salient when one looks at the diversity of deployment scenarios and requirements with low-power networks. As I have exemplified, technical and organisational choices may vary significantly from an environmental monitoring application to smart agriculture or from experimental research settings to an asset tracking system. From the perspective of core-developers, the challenges of building infrastructure transcend institutional boundaries and limit their scope for manoeuvring. The modifier distributed foregrounds such extended ambit of infrastructuring. In this context, rather than framing scaling up as a matter of strategic management and alignment of interests between multiple stakeholders, it is perhaps more useful to view it as a delicate balancing act between control and flexibility. While at the periphery, actors struggle with their very own technical and organisational challenges, core-developers leverage a range of technical features to enable and constraint autonomy and customisation.

These emerging configurations of network provisioning and service delivery have sought, in many respects, to resemble the decentralised origins of the Internet. As such, they have been framed as democratic, horizontal and with no single point of control, thereby departing from the conventional top-down approach of building internet infrastructure. The distributed mode of infrastructuring emphasises the absence of strong control mechanisms and the organic (and perhaps chaotic) way in which networks are scaled up. As an analytical concept, it not only illustrates processes of decentralisation, but also more generic processes of unbundling, decoupling or outsourcing of key activities.

The concept of information infrastructures, which grew out of investigations of information systems for scientists, is also pressingly in need of being revisited. The advent of wireless sensor networks, cloud platforms and technologies for analysing and processing large amounts of data, as well as the popularisation of practices such as data-science, data-mining and analytics are signalling a turn to a data-centred political economy (Strasser and Edwards, 2017; Flyverbom, Deibert and Matten, 2019; West, 2019). The status of data as a new commodity has permeated industry, academia and policy agendas in the last two decades and has raised questions about the reconfiguration of business models, professional and scientific practices, infrastructures and sources of power (Lyon, 2014; Ruppert, Isin and Bigo, 2017; Gidaris, 2019; Zuboff, 2019). The internet of things emerges in this scenario as a key enabler of pervasive data collection and mass surveillance. This issue is particularly salient when looking at the context of low-power networks working at low data rates but intended to support the aggregation of large datasets. Given the ultimate purpose of IoT systems to leverage data for purposes of monitoring, automation and prediction, it seems fitting to speak of 'data infrastructures' to single them out in the map of information infrastructures. Similar attempts to emphasise the shift towards widespread digitisation and systems of data acquisition and monitoring can be found in labels such as 'sensing infrastructures' or 'smart infrastructures' (see Hoult *et al.*, 2009; De Cristofaro and Soriente, 2011; Ogie, Perez and Dignum, 2017).

Recontextualising users: theoretical and practical implications

In this thesis, I have argued that the pervasive descriptor 'users', albeit omnipresent in the literature and technology discourse, is an inadequate analytical term to capture the uneven degrees of involvement of different actors in settings with high degrees of user participation in technology production. This shortcoming becomes more salient when the inputs of so-called users are actively sought after for the generation of innovation, but also, as the act of 'using' becomes conflated with practices of design, development, implementation, configuration and monitoring. Such blurring of the identities and practices commonly ascribed distinctively to users and designers has been long explored in STS and studies of innovation. In conceptualising users, STS scholars have amply problematised the diverse and often conflicting roles of actors directly and indirectly associated with technology production and use (Oudshoorn and Pinch, 2007; van Oost, Verhaegh and Oudshoorn, 2009; van den Scott, Sanders and Puddephatt, 2016). Authors in this vein have invited us to carefully avoid an *a priori* divide between designers and users and remain attentive to the existence of non-users and implicated actors (Wyatt, Thomas and Terranova, 2002; Wyatt, 2003; Clarke, 2005). Building on this lineage, this thesis contributes with new evidence to advance the study of the user in STS. Sites such as TTN shed new light on the extended scope of action of users which manifests in the rather advanced requirements for the involvement of external actors in various infrastructural development, implementation, operation and data collection processes. In these settings, actors located in the supply side seem increasingly to construct their primary 'users' as partners, developers, members, contributors, initiators, integrators and a wealth of active roles.

Following Sally Wyatt (2003) and Adele Clarke (2005), non-users and implicated actors are also relevant for developing a more substantive description of actors in the context of IoT. In doing so, one should recognise not only those who are knowledgeable/powerful enough and directly confronted with networks and artefacts. Some of the end-users, 'data subjects' or beneficiaries of smart services and information systems may in fact have fewer opportunities to engage with technical aspects than the more advanced users. Furthermore, inconspicuous sensor networks also give way to the possibility of unintended 'users', who may inadvertently become implicated in systems of data collection. In the age of surveillance, ubiquitous sensors used for occupancy monitoring systems, for example, may incidentally (and covertly) collect data from unaware subjects and passers-by, who may or not be the ultimate beneficiaries of the products and services of the IoT systems (Domínguez *et al.*, 2020). Yet, despite their marginal involvement, knowledge about those implicated actors could also be highly valuable for informing infrastructure development and regulation.

While the focus of this study has been placed on advanced users directly involved in innovation activities, end-users, implicated actors, and non-users make up the genealogy of users in the IoT.

Concurrently, the extended scope of action of users is a call to move beyond the broad notion of 'user-innovation' (c.f Bogers and West, 2012; von Hippel, Ogawa and de Jong, 2011) by breaking down the implicit or explicit user-producer divide contained therein. In contexts of distributed infrastructuring, innovation can in turn be viewed as a collective achievement; an outcome of the complementary competencies of an ecology of actors inhabiting an ecosystem many of which may be typically bundled up simply as users. Generative data infrastructures are exemplary of such complementarities insofar as they support the generation of new products and services at the edge while lending themselves to continuous infrastructural improvements. Here, the members of an *innovation collective* rely on tacit and concrete mechanisms of learning, coordination and rewards in order to succeed. Such a disorderly understanding of innovation departs from the Schumpeterian strong focus on individual actors (be they inventors, entrepreneurs or firms) as the foremost drivers of innovation and the significance of adoption and diffusion as the prime markers of success. Readers might contrast this view on users with conceptual framings that take into account emerging user-technology relations stemming from digitisation processes such as 'digital innovation' and 'platform ecosystems' (Yoo, Lyytinen and Jr, 2008; Yoo *et al.*, 2012; Monteiro, Pollock and Williams, 2014; e.g. Hanseth and Bygstad, 2018; Plantin *et al.*, 2018; Plantin, Lagoze and Edwards, 2018).

A more nuanced vocabulary is proposed as a way to make visible the multiple and uneven positionalities and responsibilities of those 'users' explicitly summoned into technology production. For the sake of exposition, I have employed terms such as non-conventional actors, members, experts, contributors, allies or advanced users' as shorthand to differentiate their distinct identities and roles relative to that of 'end-users'. In the realm of IoT, if only instructive for other contexts, I have also referred to them in terms of their praxis, namely software developers, hardware developers, network implementers and system integrators.

Mapping out distinct forms of user involvement is crucial to identify opportunities for design and policy interventions. An understanding of how users and other non-conventional actors contribute to shaping internet infrastructures and applications might be a valuable input in policy and regulation debates. In the context of internet connectivity, for instance, regulatory frameworks and policy have historically neglected the possibility of decentralised telecommunications infrastructure in favour of large commercial incumbents. Besides sparse incentives and free radio spectrum allowances, a big business-oriented view has been widely dominant in the drafting of regulation and policy for the Internet (De Filippi and Tréguer, 2016). In the case of broadband, advocates and researchers of wireless community networks have been relatively successful in problematising these issues by bringing users to the fore and demonstrating the feasibility of bottom-up approaches (Srivastava *et al.*, 2017; Song, 2018).

While in the broad rubric of internet studies 'users' have long been an intelligible unit of analysis in qualitative and quantitative research, the IoT, distributed data infrastructures and platform ecosystems call for careful consideration of the agency of the actors involved. In recent years, the theme of decentralisation has gained fairly more prominence if only owing to the industrial trends towards distributed architectures, modular provision of services and distributed ledger technologies (such as blockchain). In the European context, decentralisation of infrastructure has been included as a key theme of enquiry (albeit purely in technical terms) in the roadmap of the Next Generation Internet Initiative. The 'decentralisation of infrastructure' has been framed as 'the trend towards distributed and edge computing, where resources are not located en-masse in one location, but spread over a wide area. The degree of infrastructure decentralisation ranges from fully centralised to distributed, reflecting the increasing influence of edge computing and IoT devices (the so-called "edgification")' (Taylor and Boniface, 2017, p. 3). Under this light, the new repertoire of challenges seems to revolve around issues of data management, scalability and efficiency, legislation, user participation and interoperability (Overton, 2017). Still, while the participation of users and citizens is a recurring aspiration in policy debates, there is a dearth of evidence and theoretical work around the challenges involved with constructing and scaling-up decentralised data infrastructures. A more detailed recognition of the role of users is a step towards bridging this gap to move beyond a view of users simply as recipients or beneficiaries of technology or rich sources of data.

As demonstrated here, a range of non-conventional actors, including users, might in fact actively shape emerging infrastructures through their professional practices.

Following the work and following the problems: methodological contributions

Since Star's (1999) paper on 'The ethnography of infrastructure', a wealth of empirical work has contributed to the shaping of infrastructure studies as a field in its own right. Methodological challenges have been a recurring theme given the serious difficulties of studying systems which operate in the background and are made to span across time and geographical borders. For the ethnographer of infrastructures, in particular, collecting data from multiple sites and over several years demands not only an enduring commitment to the field but a strategic use of resources. Critics of short-term and localised studies of infrastructure have made a compelling case for longitudinal, multi-site and concatenated studies (Williams and Pollock, 2012; Hyysalo, Pollock and Williams, 2018). Yet while extended research may be highly desirable, the study of infrastructures remains fraught with uncertainty and the various practical limitations of research, notably in regards to funding and time. Quite strikingly, the inception of information infrastructures has been largely understudied, and concurrently, the possibility of infrastructure failure or stagnation. Being mindful of the hurdles of accessibility and the institutional constraints of research funding and duration, research designs could profit hugely from an attentiveness to key moments of change found in early decisions, idiosyncratic sites, odd encounters, failures, dilemmas and conflicts. This thesis is instructive of how information infrastructures can be feasibly studied based on early-stage observations, hands-on ethnography and the use of digital content and tools. Some of the techniques and resources employed here are helpful to scholars interested in the study of infrastructural systems and contribute to the ongoing methodological debate within infrastructure studies.

Edwards et al. (2009, p. 365) argued that infrastructure appear as 'both an all-encompassing solution and an omnipresent problem, indispensable yet unsatisfactory, always already there yet always an unfinished work in progress'. Such sense of incompleteness and constant change seems staggeringly stronger during the nascent phases where objects and social formations are remarkably volatile, manifesting as provisional or workable to various degrees in some places and just as discursive representations in others. This study examines a very early stage in the construction of a new data infrastructure at a point where a wealth of options was still being factored in, negotiated and trialled. While I encountered concrete objects both finished and provisional, I was also confronted with myriad *potential* objects in the form of plans, diagrams, expectations, roadmaps and predictions. At the same time, I was faced with a fast-evolving world and an overwhelming number of events and developments unravelling simultaneously and at different remote locations. Studying the early life of infrastructures offers an rare opportunity to observe change, but it demands for effective methods.

Given the need to collect sufficient data variability in time and space, I looked for methodological choices aimed at dealing with the changing landscape and with the various formats of evidence available and accessible through the lens of ethnography. Publications on internet research and digital methods are frequently being revisited in light of the rapid evolution of sociotechnical systems and the rise of new *genres* of social interaction. Voluminous editions of research methods published in the last decade offer a plethora of good practice recommendations; new techniques, tools and concepts; and ethical considerations stemming from 'state-of-the-art' research (Fielding, Lee and Blank, 2008; e.g. Hewson and Laurent, 2008; Hughes, 2012; Snee *et al.*, 2016). Yet while much of the existing repertoire of methodological knowledge can be taken on board in new terrain, there is very little reference material for engaging with the ethnographic study of infrastructures. Familiarity with the canons of qualitative research and previous studies of information infrastructure was essential for devising a preliminary research design, but flexibility and a strategic use of data sources were the most critical aspects of the research strategy. In this study, I developed a strategy for conducting a multi-site enquiry of the construction of data infrastructures which takes advantage of the affordances of new digital tools and media. Some of the tactics and techniques developed for this study are transferable to other research projects and are instructive for contemporary STS ethnographies and a growing repertoire of digital methods.

I would like to draw attention in particular to the distinct techniques of participant observation which were designed to compensate for the salient inefficiency of conventional observation when it came to capturing computer-based work and geographically dispersed sites. Following Marcus' (1995) framing of multi-site ethnography and his emphasis on focused observation such as following the people, the thing, the metaphor, the story, my observation routine entailed *following the work* and *following the problems* with the aim of accessing multiple sites and computer-based work (such as coding) in an efficient way. The case study entailed two cohorts of informants (core-developers and local contributors) and multiple remote sites. Gathering data about both cohorts was accomplished through a combination of situated observation and virtual observation on digital channels. Developers' strong reliance on software and digital tools for carrying out their daily duties, rendered digital media essential means for observation and researcher-informant interaction. In addition, the rationale underpinning the research strategy was that in order to understand the everyday work of developers and prompt relevant questions, it was necessary not only to follow the traces of work but to engage with it practically. This choice entailed an engagement with training and experimentation and a familiarisation with the working tools, the technical jargon and the various means of communication. The aim of tuning in with the routines of informants was not to become a native (which was, in fact, a risk to be mitigated), but to build faithful accounts of their experience as developers and network architects. Training and experimentation are time demanding affairs, and thus it is important to find a balance between understanding the 'tricks of the trade' and leaving space for notetaking, data analysis and reflexivity.

Following the work entailed observation conducted online, offline and on a real-time basis. Activities such as writing and debugging code, frontend development, data analysis can be, at least partially, observed through routine team discussions and sharing which may take place online or during face-to-face meetings and breaks. Furthermore, taking advantage of physical co-presence allows for opportunities for clarifications and casual face-to-face interaction which may reveal unexpected threads of enquiry.

The luxury of on-site observation however may not be possible if the research design aims to incorporate multiple geographically dispersed sites, not least due to logistic, time and even circumstantial constraints of doing research in transnational contexts.

The contemporary conditions of research demand (and allow for) creative uses of digital tools in order to reduce travel costs while ensuring the quality of data. There are several ways in which ethnographers can remotely grasp the work on the ground through the use of digital media. Real-time chats and forums, in particular, offer a rich source of data when they are populated and moderated regularly. The challenge however lies on where to focus the observation? And how to combine qualitative questions with large streams of data? In this study, both core-developers and peripheral actors used the internet intensively to resolve questions, provide peer-to-peer support and produce and consume digital resources. The use of these channels was however highly unpredictable with irregular use behaviours depending on the types of problems and frequently contained lengthy threads on technical issues and with content generated mainly by moderators, initiators and core-developers.

These issues posed challenges in regard to the value of the data for the research questions. Rather than collecting a large corpus of data and digging for clues within long conversation threads, a key tactic was to focus on what the problems experienced by remote actors revealed about their efforts on the ground. It was at interstitial moments such as struggling with code and configurations; sharing blueprints, documents and photographic evidence; and reporting back where learning mechanisms and local infrastructuring efforts were most visible. I describe this technique as *following the problems*. My intention with this approach was to identify problem categories (e.g. technical, organisational, political, or financial) as well as the different mechanisms to deal with them (e.g. peer to peer support, sharing good practice, following up). Grasping the work of remote sites was complemented with interviews, some of them conducted online, which offered a space to enrich the data and fill in the gaps. This approach was helpful to foreground the work of remote actors and the processes of learning associated with distributed infrastructuring without aiming to produce comprehensive accounts of each site. In tandem with other methods of observation, this technique is helpful when travel to various remote sites is impeded as it offers a means to access a large number of sites in an efficient manner. Finally, while the amount of data collected through digital means may be daunting, the indexability of these data allows for enhanced ways to query the data through the use of available software tools for qualitative data analysis.

Finding meeting points between digital methods and multi-sited ethnography pushes the frontiers of the empirical study of information infrastructures and invites us to reflect on how the different sites interrelate? What are the boundaries of communities of practice? How do we identify relevant data? How shall 'sites' be constructed? And what are the implications of time and timing in regards to fieldwork?

Limitations and future research

In this section, I reflect on the limitations of this research which stem both from the very nature of the object of study and from the exigencies of conducting fieldwork in time and resource-constrained conditions.

First, I would like to touch on the restrictions in regards to scope and sampling. The range of sites and informants contemplated in the study was constrained both by issues of access and the timing of my immersion in the field. On the one hand, given the geographically dispersed landscape, travel was restricted to a reduced number of sites within Europe and was organised in an opportunistic way taking advantage of physical proximity. Moreover, cross border mobility was an issue I faced as a non-European student based in the UK. Due to a 90-days visa restriction in the Schengen area, I accommodated separate field trips spread across an extended period. On the other hand, despite the global scope of the initiative from the outset, at the early stages, local implementations were concentrated in Europe and more precisely in the Netherlands. Other geographies beyond Europe, particularly those in the Global South, have been underrepresented in this study due to their marginal incidence at the time of data collection.

Similarly, there was a difficulty in recruiting female participants owing to their marked underrepresentation in the discourse, events and the overall activity. Quite unfortunately, all but a handful of participants interviewed in this study were men. In hindsight, I could have made more efforts to recruit female participants for the study, and also pose questions of gender misrepresentation to my informants. The gender disparity, along with other dimensions of exclusion, is however not unique to the contexts of this study considering the general predominance of men in engineering and cognate disciplines and in the ICT industry (Cukier, Shortt and Devine, 2002; Evans *et al.*, 2007). While the sampling may well reveal the class, racial and gender contours of tech communities, this issue needs to be further explored empirically. Looking into the quantitative demographic data from the universe of participants would be a good starting point to look into this issue.

These shortcomings necessarily bear on the generality of the theoretical claims of this study but also on the characterisations of universality, openness, heterogeneity and globality that are very often attributed to information systems and which ought to be appraised with a critical lens. New evidence has emerged since the closure of the fieldwork of this study: the available macro statistics hint at a growing installed base also in the developing world (The Things Network, 2019c; LoRa Alliance, 2020) and a larger aggregate number of members and contributors. Such a scenario offers an opportunity for future research where there is much to be gained from coming full circle with the ambitions of 'multi-sitedness' by incorporating realities beyond the West, but also from reaching out to critical perspectives at the intersection of STS, postcolonial studies and feminist approaches (Wajcman, 2010; Harding, 2011; van der Straeten and Hasenöhrl, 2016).

A second limitation concerns time. Infrastructure scholars have emphasised on the need to trace technological innovation historically and think about the long-term while studying current developments (Edwards, 2002; Ribes and Finholt, 2009; Karasti, Baker and Millerand, 2010). Similarly, the study of technological change has been predicated by some authors on the need to account for 'long-enough' periods of evolution. Longitudinal studies and biographical approaches have been promoted as adequate ways to capture extended life cycles with discernible moments of change. One method has been to piece different pieces of research together and in that way 'build a comprehensive understanding of the evolution of a technology – encompassing both technology design and implementation/use – and how it is shaped by its specific historical context across multiple social locales' (Pollock and Williams, 2009, p. 80). It is nonetheless problematic to establish *how long is long enough* to observe significant variability in the evolution of infrastructures. Even more pressingly, how longitudinal evidence is to be obtained and planned for in advance within the boundaries and resource constraints of a standalone research design remains an open matter.

In this study, time has been a central dimension of analysis, but at the same time, a scarce resource in the research design. I have located the phenomenon in a broader history of the internet by taking into account past developments, cultures and contexts. However, fieldwork spanned only a relatively short period of under three years. To moderate this issue, I complemented the ethnographic exploration with existing secondary historical data, and hence, the overall timeframe of the analysis comprehends approximately four years. Given the fast pace of development, I witnessed numerous changes and important milestones in this period wherein different artefacts and facets of design, development, and implementation came to the fore. Still, while I engaged with different kinds of developers, implementers and integrators, time was not enough for following up the evolution of communities and incorporating end-users and more stable applications in the analysis. Similarly, key aspects of infrastructuring such as maintenance in its different forms need to be observed and documented more in detail. In this sense, this thesis only accounts for a portion of an ongoing phenomenon. Although further exploration is perhaps the obvious corollary of any ethnography, I would emphasise mainly on the value of looking into advanced stages of development and implementation and scrutinise the various forms of *use in the wild*.

Finally, in reading the case of The Things Network, it is important to consider how this initiative is embedded in a wider array of institutions; for instance, in the LoRaWAN ecosystem as well as under the broader rubric of the internet of things. In this study, I have constructed the case as an ecosystem of core-developers and peripheral community members and independent actors. Beyond the boundaries of the case, there exist myriad other actors who are implicated in the processes explored in this study. These include standard development consortia, telecoms, hardware and software vendors, platform providers, competitors and regulators. The ethnographic sensibility offered an opportunity to engage at various interstitial moments with these complementary actors, and hence this thesis is not blind to them. However, external institutions were not systematically researched during fieldwork, and therefore this account does not offer a holistic picture of this highly complex terrain. This is a matter of scale that seems to outflank the ambit of ethnography and where a multilevel perspective could prove valuable. Following Edwards (2002), a linking up with the meso and macro levels, taking into account national, regional and global matters of governance, regulation, culture and politics may well be a fruitful path towards supplementing this piece of work. One way to do this would be to engage with quantitative methods to analyse longer term change and assessing the value of counting (nodes, traffic, participants and events) as a means to measure and interpret success.

Final remarks

I would like to end by reflecting on some of the ethical issues that surround the increasing focus on data-oriented systems, which mark other profitable avenues of research that could build on the findings of this study.

Previous efforts on decentralisation of internet infrastructure have brought to the fore pressing questions in the wake of a 'global information society' including issues of access, neutrality, privacy, trust and different forms of digital divides. Alternative, community-led and bottom-up models have emerged as possible remedies to some of these problems and have evidenced the need for new regulation at national and regional levels (Belli and De Filippi, 2016). With the advent of the internet of things, these problems are still present if not exacerbated, and new ones are arising. While the virtues of smart infrastructures have been enthusiastically positioned in the public discourse, they have also brought about a new set of concerns around privacy, security and human agency. These issues are further compounded by the growing concentration of power in the information economy, the consolidation of business models based on data-enabled systems of prediction and automation, and the possibility of sensor networks to become taken-for-granted and normalised.

The idea of decentralised systems seems to be a popular counter-mainstream proposition in the ICT industry, and despite their numerous downsides, these approaches seem to easily lend themselves to idealised narratives of openness, civic participation and empowerment. Yet, certain models of governance such as those relying on the 'platformisation' of information systems may engender problematic dynamics of data extraction and power asymmetries between beneficiaries and the gatekeepers of systems. Further empirical and theoretical work on alternative forms of organising infrastructure therefore arises as a promissory site of enquiry to deal with some of the emerging ethical questions. The internet of things along with the shift towards a data-oriented paradigm has implications for many facets of life in post-industrial societies, including the home, healthcare, urban spaces, agriculture, supply chains, mobility energy systems and scientific practice. While the scrutiny of these systems is imperative, decentralised and distributed infrastructures also offer an opportunity to critique entrenched sociotechnical systems and the consideration of new forms accountability, participation, ownership and control in technoscientific production.

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Appendix I - List of interviews

Table 8: List of interviews

Number	Role	Field/industry	Background	Date	City/Region
1	Initiator	IoT products and services	Software engineering	28/02/2017	Den Bosh
2	Core member	Third sector Smart cities	Landscape architecture and planning	01/03/2017	Rotterdam
3	Core member	IoT product design	Industrial engineering	03/03/2017	The Hague
4	Initiator	IoT products and services	Computer science Business development	23/03/2017	Wallonia
5	Contributor	IT and software	Product Engineering	31/03/2017	Canada*
6	Initiator	Research	Physics Technologist	25/04/2017	Copenhagen
7	Initiator	Telecom services	Radio and telecommunications	03/06/2017	Zurich
8	Initiator	IoT Innovation Smart cities	Business development	04/07/2017	UK*
9	Core member	Research	Computer science research	03/09/2017	The Netherlands*
10	Core member	IT services	Mobile and web development	03/09/2017	Flevoland
11	Core member	IT and education	Electronics IT services	03/10/2017	Eindhoven
12	Initiator	IoT products and services	Software and hardware development	14/03/2018	The Netherlands*
13	Initiator	IT and IoT services	Software development	30/08/2018	New York
14	Initiator	Research	Academia Radio and telecommunications	23/10/2018	Madrid
15	Initiator	Private business	Electrical engineering	24/10/2018	Basel
16	Tech lead	IoT infrastructure	Business development	16/01/2019	Amsterdam

17	Implementer	Telecom services	Telecommunications engineering	22/05/2019	Aberdeen
18	Contributor	IoT products and services	Electronics engineering	22/05/2019	Edinburgh
19	Founder	IoT infrastructure	Industrial engineering	26/06/2019	Amsterdam
20	Implementer	IoT infrastructure, products and services	Business development	10/11/2019	Germany*

*The city is not provided to protect anonymity

Appendix II – List of interview questions

TTN contributors

Background

1. Thank you for participating in this interview. First of all, I'd like to ask you about your background and how you got involved with the Things Network in ____

Governance

2. Is there a legal entity behind it? Or are there any plans to establish one? / How has the legal structure of the community evolved in the last year?
3. How is the network governed at the local level? Who takes part in the decision making process?
4. How is ownership of infrastructure managed?
5. Is there a need or motivation for decentralising more components of the network (network servers)?
6. Compared to commercial top-down structure with service providers, what is the advantage of having a more distributed organisation and decision making?

Quality of service

7. How important is to provide services that are of similar quality to commercially available services? Are these type of networks reliable enough for critical services?
8. What are the fixed sources of funding? What other sources are there?
9. Do you think community-led IoT networks can compete with commercial service providers?

Projects and applications

10. What kind of projects are there currently being developed or in the pipeline?

Community

11. Beyond TTN's manifesto, is there a shared ethos or guiding philosophy that the community shares and signs up to?
12. What have been the main achievements in the community since last year?

Users

13. Who is the intended audience/participants/users of the network?
14. As an initiator (leader). How do you relate to them? Are they clients, users, potential members?

Funding and sustainability

15. Once an organisation has achieved a critical mass of users, it is common that these are acquired by large capitals. Would that be the case of the Things network and its local communities?
16. Otherwise what makes this organisation different?
17. Will this community locked-in to TTN and LoraWAN?

Related IoT projects and initiatives

Overview

1. Can you give a brief overview of what the project entails, the motivations and its timeframe?

Governance

2. How is the organisation behind the project structured?

Users

3. Can you describe who are the users of the intended product or service?
4. How do they contribute or participate?

Funding and sustainability

5. Is this project a one off effort? Otherwise what are the paths to sustainability with this project? Is there a plan in place for ensuring continuity of the project?
6. .If so, what would be the main sources of funding? Or is there a business model

Other open questions depending on the project

Founders

1. With the new architecture, what are the means of steering the global network in terms of future growth and buy-in from current as well as new partners?

2. What is the difference between scaling up public networks vs private?

    a. Can public networks be (at least in theory) robust and stable deployments for innovation? Or are they conceived more as a transitional testbed for learning and prototyping?

3. In general, how would you describe TTN's current strategy for scaling up the network?

4. What would you say are the different options for user involvement in the ecosystem?

5. A lot of validation happened in earlier stages with forum discussions with the members and sharing the strategic decisions and roadmaps. What has changed in that regard?
    a. Has the model reached a stage where validation is a lower priority or is validation from members still relevant in the agenda?

6. What happened to the original manifesto which served as a sort of soft code of conduct for members and is not visible or pointed at anymore?
    a. Was it replaced by any other form of agreement or licence?
    b. Is it expected that communities establish their own local rules?

7. It could be said that LoraWAN sparked the idea of the Things Network. But does that mean TTN is dependent on the success of LoRaWAN as a standard?
    a. Could there TTN exist beyond LoRaWAN?

8. Where does hardware sit in the equation currently? Is there a plan to keep promoting the manufacturing of low-cost devices?
    a. If so, who would take up this role?
    b. Is there a lot of hardware (product) innovation in the community? Which groups are best positioned to take up this activity?

9. Early in the design of TTN, there were discussions around how to enforce a fair use of a free resource (i.e. airtime). One proposition was to measure the rate of contributions/extraction of resources per member, which was eventually discarded. What has been the learning so far? Is this still a concern or could be in the future?
    a. If so, how could this be addressed?

10. How would you describe the strategy for long term sustainability of the Things Network Foundation?

    a. Does the sustainability of the global network depend on the survival of the local communities, and therefore on their capacity to be sustainable and credible groups?

11. Are there any plans to align to other "conventional" business models eg. of data commodification or platformization?

12. Is there any clash between the commercial and the non-profit interests of the initiative?

Appendix III – Documents exchanged with participants

Interview Consent Form

Research investigator: Andrés Domínguez

Research Participant's name: ___________________

Thank you for agreeing to be interviewed as part of the above research project. Ethical procedures for academic research undertaken from UK institutions require that interviewees explicitly agree to being interviewed and how the information contained in their interview will be used.

This consent form is necessary for us to ensure that you understand the purpose of your involvement and that you agree to the conditions of your participation. You would therefore read the accompanying information sheet and then sign this form to certify that you approve the following:

- the interview will be recorded and a transcript will be produced
- the transcript of the interview will be analyzed by Andrés Domínguez as research investigator
- access to the interview transcript will be restricted to Andrés Domínguez and academic colleagues with whom he might collaborate
- the actual recording will be kept by Andrés Domínguez
- any variation of the conditions above will only occur with your further explicit approval

With regards to being quoted, please initial next to any of the statements that you agree with:

	I agree to be quoted directly.
	I agree to be quoted anonymously with certain identifying details (position, role) included.
	I agree to be quoted anonymously with no specific identifying details included.

All or part of the content of your interview may be used:

In academic papers, policy papers or news articles

In other media that we may produce such as spoken presentations

By signing this form, I agree that:

I am voluntarily taking part in this project. I understand that I don't have to take part, and I can stop the interview at any time;

The transcribed interview or extracts from it may be used as described above;

I have read the Information sheet;

I don't expect to receive any benefit or payment for my participation;

I have been able to ask any questions I might have, and I understand that I am free to contact the researcher with any questions I may have in the future.

____

Printed Name

______________________________________ _____________________

Participants Signature Date

Contact Information

If you have any further questions or concerns about this study, please contact:

Andrés Domínguez
Science Technology and Innovation Studies
School of Social and Political Science
The University of Edinburgh
Chrystal Macmillan Building
15a George Square, Edinburgh EH8 9LD
Tel: +44 (0) 1316514274
E-mail: andres.dominguez@ed.ac.uk

Information Sheet

Researcher: Andrés Domínguez

About the Project

With the advent of the Internet of Things, developers and users at various levels have an opportunity to engage collaboratively in designing "connected things" as well as the information infrastructure to support them. Such involvement brings about a challenge to traditional models of innovation. A sociotechnical approach can be used to delve into how civic participation shapes the Internet of Things from the bottom-up. This research project comprises an exploration of decentralised information infrastructures using on-site strategic ethnography and semi-structured interviews. The aim of the study is threefold: first to present an account of the phenomenon from a sociotechnical perspective; second, to offer explanations for the occurrence and survival of such bottom-up initiatives; and third, to understand innovation originating from users and communities of users

Who is responsible for the data collected in this study?

Andrés Domínguez, PhD student at the University of Edinburgh, will be responsible for the data collected in this study. Fieldwork notes, interview recordings and transcripts and openly available online content will constitute the main form of data to be sought. Additional information, such as data bases, source code, photography and video may be collected by the researcher if these are provided willingly by research participants.

The information will only be used by the researcher and any academic colleagues with whom he works. The raw data will not be shared with any other organizations.

What are the risks involved in this study?

Your contribution may be anonymized, to various degrees described in the consent form. There are few risks involved in this study given the non-confidential, public nature of the behaviour studied and the voluntary nature of participation.

What are the benefits for taking part in this study?

The study will provide both the TTN community and academics with a socio-technical account of infrastructures and bottom-up innovation from the tradition of Science and Technology

Studies. This school of thought challenges longstanding views on innovation particularly those coming from economics, management science or business schools. This particular research project seeks to offer a contribution to the understanding of user-technology relationships, and innovation in the Internet of Things. The findings of the research are of interest for the study of information infrastructures as well as to inform design and governance.

What are your rights as a participant?

Taking part in the study is voluntary. You may choose not to take part or subsequently cease participation at any time. You may request information about the nature of the research at any time.

Will I receive any payment or monetary benefits?

You will receive no payment for your participation. The data will not be used for commercial purposes. Therefore, you should not expect any royalties or payments from the research project.

For more information

If you have any further questions or concerns about this study, please contact the principal research (contact details on page 1). In case of any concerns, you may also wish to contact his supervisor:

Andrés Domínguez
School of Social and Political Science
The University of Edinburgh
Chrystal Macmillan Building
15a George Square
Edinburgh
EH8 9LD
Tel: +44 (0) 1316514274
E-mail: andres.dominguez@ed.ac.uk

Appendix IV – Timeline of events

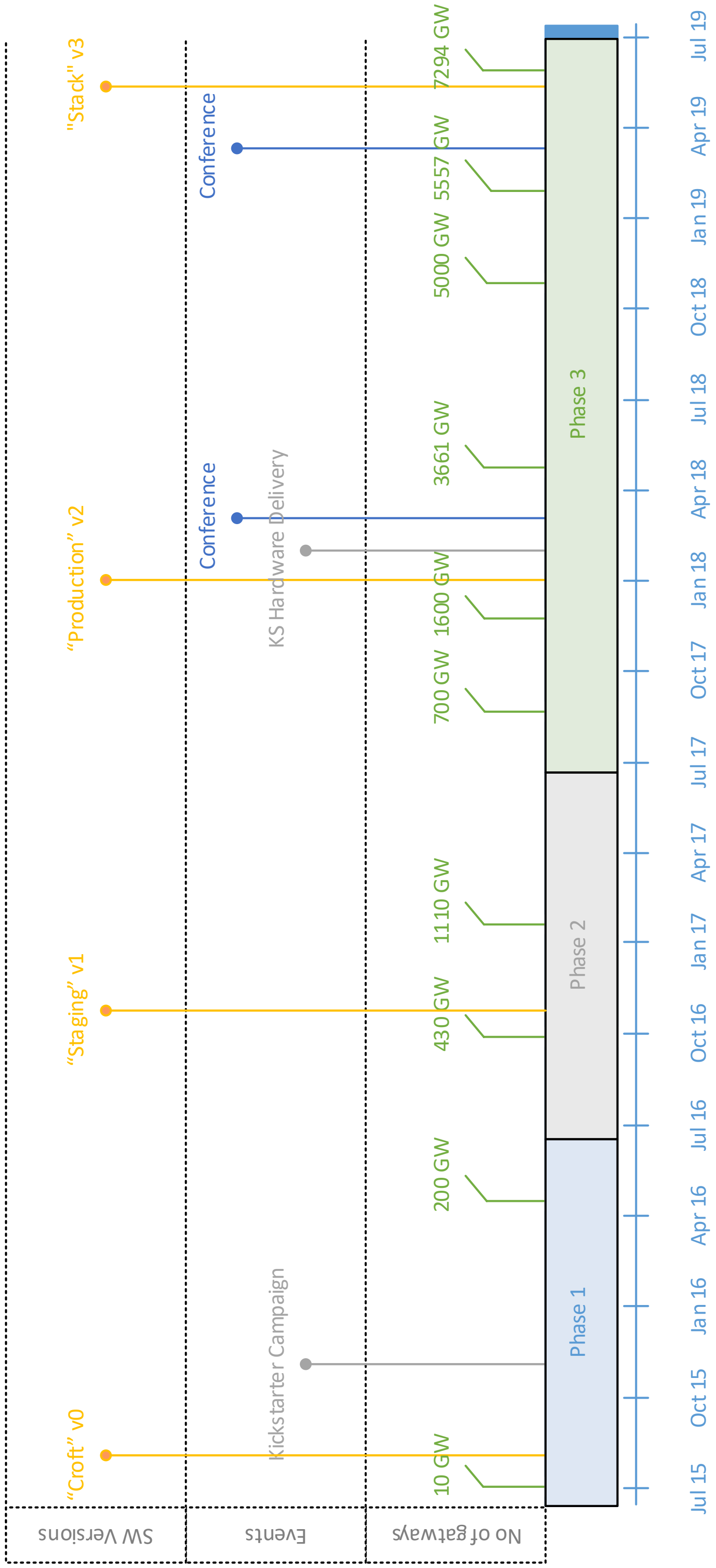

Figure 22: Timeline of events

Appendix V – TTN Roadmap 2016-2017

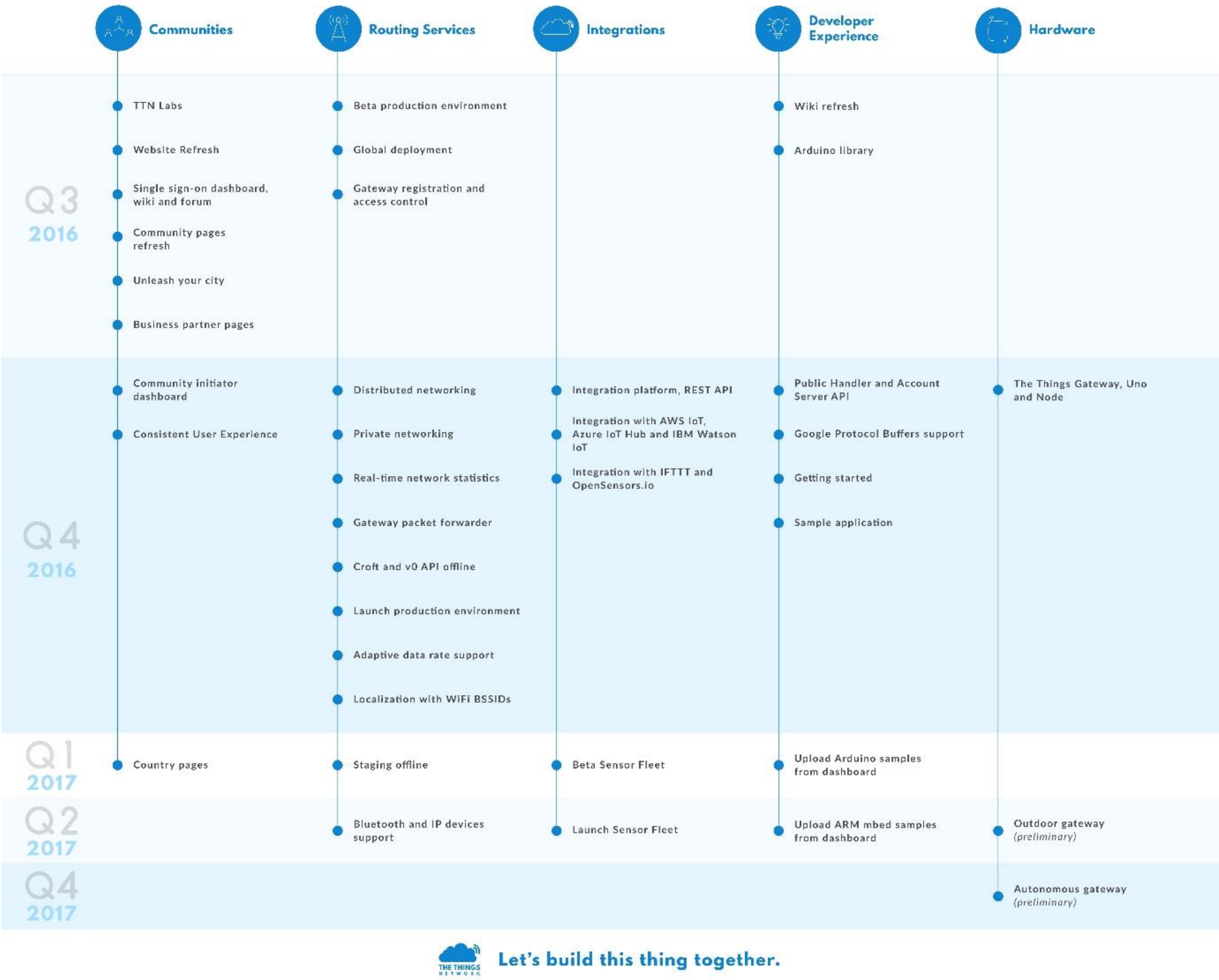

Figure 23: TTN Roadmap 2016-2017 (internal communications)